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Citation:

Marino, MD and Weng, TH and Li, KC (2017) Exploiting Dynamic Transaction Queue Size in Scalable Memory Systems. *Soft Computing*. ISSN 1432-7643 DOI: <https://doi.org/10.1007/s00500-016-2470-x>

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Document Version:

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Exploiting Dynamic Transaction Queue Size in Scalable Memory Systems

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Abstract

In order to increase parallelism via memory width in scalable memory systems, a straightforward approach is to employ larger number of memory controllers (MCs). Nevertheless, a number of researches have pointed out that, even executing bandwidth-bound applications in systems with larger number of MCs, the number of transaction queue entries is under-utilized - namely as shallower transaction queues, which provides an opportunity to power saving. In order to address this challenge, we propose the use of transaction queues with dynamic size that employs the most adequate size, taking into consideration the number of entries utilized while presenting adequate levels of bandwidth and minimizing power. Experimental results show that, while saving up to 75% number of entries, the introduction of dynamic transaction queue mechanism can present savings up to 75% of bandwidth and 20% of rank energy-per-bit reduction compared to systems with 1-2entries. With such promising results, it can be aimed and incorporated in modelling methodologies directed to the design and evaluation of new generation embedded systems.

Keywords: memory, controller, dynamic, transaction, queue, scalable.

1. Introduction

The increasing number of cores in current embedded and traditional multicore chip design has put an unprecedented high pressure on memory systems. As efforts to approach the I/O pin scalability - determinant factor of memory controller (MC) scalability, scalable memory systems utilize memory interfaces that allow I/O pin reduction and large-magnitude data rates to achieve MC scalability.

Double-data rate (DDR) memory is the most employed dynamic memory system (DRAM) organization in current multicore systems, where memory DRAM chips share and enable address, decode, and I/O pins, and a memory rank, or simply rank - commercially called as dual inline memory module (DIMM). It is formed by several bank chips enabled in parallel, so that the total width is obtained when aggregating the width of each one of them. e.g., a 64-bit width is achieved by aggregating 8 banks of 8 bits. This context is illustrated in Figure 1.

Traditional Double-data rate (DDR) memory design has been focused on memory frequency. That is,

the application of higher clock frequencies to memory formed by set of memory banks with data output aggregated and sharing addresses. Clock frequency scaling (FS) applied on these traditional systems have permitted DDR family generations been responsible to bandwidth improvement. For instance, a factor of 10x larger clock frequencies has been applied along DDR family generations [1]. Since memory power usage is proportional to frequency, scalable memory systems also present the advantage of power, by shifting the traditional focus on FS to memory width, represented by MC and rank scalability, by assuming one rank for each MC or memory channel [2].

Comparatively to traditional solutions, advanced memory interfaces explore significant larger number of MCs, or MC counts. These advanced interfaces rely on optical- and radio-frequency (RF) technologies that permit them to be implemented with fewer I/O pins, bringing out higher and optimized degrees of MC scalability. For instance, Corona is able to scale up to 64 optical-MCs [3] while DIMM Tree up to 64 RF-based memory controllers (RFMCs) [4].

[Figure 1 about here.]

Since MCs are scaled to the number of transaction queue in scalable solutions, entries in each MC are also scaled. As per discussions in [2], memory traffic along each MC is reduced as MCs are scaled, i.e.,

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transaction queue usage is reduced.

A number of researches present evaluations of most adequate size for transaction queues in terms of bandwidth and power [5]. Their evaluations are static ones, which do not take into consideration different transaction queue utilization rates along with the execution of applications. Conditions for dynamic sizes are discussed in [5]; however, no algorithm, implementation or evaluation of these dynamic sizes were analyzed. Therefore, a proper dynamic evaluation of the most appropriate transaction size is necessary to find the best power saving configuration that matches to the bandwidth utilization.

To advance the state-of-the art in scalable memory systems, we investigate in this paper the trade-offs of a dynamic transaction queue size to match the bandwidth utilization and minimize power consumption, with the following contributions:

1. Design a dynamic transaction queue mechanism that matches to the number of entries utilized and memory load,
2. Create a model based on scalable memory systems that has an inherent algorithm which dynamically changes all transaction queue size to match the load. This proposed model is evaluated using detailed and accurate simulation tools combined with memory bandwidth-bound benchmarks,
3. Perform evaluations on the proposed mechanism in terms of bandwidth impact under several workload conditions,
4. Evaluate rank power when utilizing dynamic transaction queues.

The remaining of this paper is organized as follows. Section 2.2 and 3 presents the background and the related work respectively, and dynamic transaction queues are depicted in Section 4. Section 5 presents experimental results achieved, and finally, the concluding remarks and future directions are given in Section 6.

2. Background and Motivation

In this section, a bottom-up description of scalable memory systems by starting with the components of a memory rank and its operations/modes is provided. Following next, with the purpose of improving bandwidth and reducing latency as mentioned in previous section, we discuss scalable memory systems interfaces that are able to scale ranks. Facts about how shallower transaction queues incur in the context of scalable memory system interfaces will also be depicted.

Before we discuss how a rank is interfaced to RF circuits, we highlight that RFMCs are used instead of typical MCs. As reported in [2], RFMC is defined as a MC coupled to RF TX/elements that perform modulation and demodulation of commands, data, clock, and addresses when performing memory operations (e.g., read and write). Signals are transmitted over the RF-interconnection between the RFMC and rank. Command, clock (CK), and address signals are demodulated at the ranks, which also modulate data to be returned to the RFMC as a read operation performed. It is illustrated in Figure 2 the context where these previous memory path elements are employed.

According to report [6], a typical MC is composed of elements, listed as: (a) front engine (FE), which processes L2 cache requests; (b) transaction engine (TE) that transforms these requests into control and data commands to be sent to the ranks, and (c) physical transmission (PHY), composed by control / data physical channels. Particularly, along with its optical or RF memory interfaces, modulation and demodulation of commands, data, clock, and addresses are performed while executing typical read/write memory operations. Along with these interfaces, signals are transmitted over the optical/RF interconnection between the optical-MC/RFMC and rank. Additionally, command, clock (CK) and address signals are demodulated at the ranks, as also modulate data to be returned to the MC when a read operation is performed. Figure 2 illustrates the context where the rank element is utilized together with an MC.

[Figure 2 about here.]

2.1. Scaling Memory Width - MC/rank scaling

In this subsection, we illustrate the performance and power motivations mentioned in previous sections when scaling memory width and rank frequency as memory design techniques in scalable memory systems.

Memory width, represented by the total rank count width, it concurrently scales as rank count width are scaled. Despite that, memory width scalability is restricted by pin scalability, as indicated in [7][2].

Typical memory interface elements employed in scalable systems are exemplified in Figure 2, such as DIMM Tree [4] and RFiof [2]. In these systems, RFMCs perform modulation of digital cache requests and demodulation of rank read operations. Similarly, ranks perform requests of write data demodulation and read data modulation. Between RFMCs and ranks, there are RFpins and RF-interconnection implemented via transmission lines, such as the ones at FR4 boards used in DIMM Tree

[4] or the set formed by microstrips, microstrip-to-coaxial interface, and coaxial cable in RFiof [2]. When an interposer is used in the motherboard implementation, RF elements can be placed.

By showing that RFpins are able to carry larger data rates, RFpin scalability is comparable to optical-pin one as depicted in [7][2], thus enabling RFMC scalability that support scalable systems and their scalable bandwidth.

As result, bandwidth achieved by scaling RFMCs is significantly higher than a typical 2-MC or 4-MC system employed in typical microprocessors [7][2][4]. For example, bandwidth achieved with 32 RFMCs in RFiof [2] is up to 7.2x higher than a 5-MC DDR-based system, assumed as a baseline in a 32-core processor configuration. Since bandwidth and latency are related based on Little's law [8], latency is likely to decrease: a notable latency reduction of 69% is obtained in RFiof [2].

Another important advantage of these scalable systems is power consumption. For example, rank power consumption of RF-interface elements (TX/RX and RF-memory channel) correspond to 3-4% of a traditional DDR3 rank in DIMM Tree [4]. That is, at the same order of magnitude of a traditional DDR3 rank. Furthermore, RFMCs can architecturally replace MCs, given their advantage in terms of power, as depicted in [7]. Given that larger bandwidths are achieved via employing larger number of MCs, energy-per-bit is likely to decrease [2].

To illustrate the need for more MCs, the behavior of rank bandwidth along with different low power memory generations is shown in Figure 4 [1]. We could observe that total rank bandwidth is still restricted in terms of magnitude, a fact that motivates the need of approaching bandwidth via MC scalability.

[Figure 3 about here.]

Recently developed and commercially available memory solutions still employ larger number of pins that can still restrict MC scalability, i.e., memory width. For instance, Hybrid Memory Cube employs 55 pins and can utilize up to 8 MCs [9]. In addition, the maximum aggregated bandwidth is 320 GB/s while each I/O-link presents individually 10 Gbit/s. Furthermore, Wide I/O 2 employs 128 bits per rank and 8 MCs, thus still MC-count restricted (total width 1024 bits) [10].

Another example of scalable solution is RFiof [2], illustrated in Figure 4b. RFiof is designed to scale to 32 RFMCs and 345.6 GB/s, using 10.8GB/s ranks. Given its lower number of pins and adoption of a conventional RF-interface (FR-board as in DIMM

Tree [4]), this technology has the potential to be scaled to make use of 64 RFMCs and ranks of 17.2 GB/s, to achieve the bandwidth of 1024GB/s (and total width of 4096 bits). The bandwidth magnitude achieved is similar by optical technologies [11][3].

2.2. Motivation

Each MC has a transaction queue, which is composed by certain number of entries utilized to store cache requests. As applications are executed, transaction queue entries are filled depending on their memory-bound behavior. Applications with intense memory-bound behavior are likely to have more entries filled, and less entries filled otherwise.

In scalable memory systems, sets of MCs and ranks are scaled to improve bandwidth and decrease power, whereas simultaneous memory transactions happens concurrently [3][7][2]. As one of motivations mentioned in section , this increase in parallelism improves throughput and decrease latencies [7][2], yet shallowing transaction queue utilization, that signifies that less entries are utilized while faster processed when compared to typical systems (with low number of MCs available).

Going further, even in the scenario where intense memory-bound applications are executed, transaction memory queues are not completely utilized [7][2]. An example for intense memory-bound applications are STREAM[12] and pChase[13], where the number of memory transactions entries occupied is reduced up to 5 times when scaling the number of MCs/ranks in RFiof [7] scalable memory system. In addition, the reports [14] [15] illustrate that intense memory-bound behavior can appear in other applications such as in genetic algorithms where the approach is via measuring the performance. The former explores the conflicting input metrics, such as cost and power consumption, and produce a guide of an effective optimization to the multimedia embedded system designers. Another example of the applications of these memory systems is likely to improve the performance of graphic processing units such as reported in [16] where a tree-based Genetic Programming could be utilized as a benchmark due to its bandwidth-bound behavior.

As conclusion from previous analysis, transaction queue entries are not completely occupied upon with memory requests, leading to its sub-utilization.

3. Related Work

Initial evaluation of transaction queue reduction in terms of power and performance impact was presented in [5]. In this paper, we advanced and im-

proved performance and power implications of shallower transaction queues presented [5], by proposing a dynamic hardware approach that matches the transaction queue size to behavior of applications.

Optical- [3] or RF-based solutions [7][2] utilize memory interface solutions to address the mentioned I/O pin restrictions that permit MC scalability [11][2]. This approach can be applied to previous scalable systems, matching the size of transaction queues to the size of the transaction tuned to the application executed.

With the challenges induced by growing number of cores in the multicore era, Udipi [11] proposed a number of hardware and software mechanisms to approach higher memory bandwidth demands via utilization of optical-based interfaces, appropriate memory organization for taking advantage of optical transmission, and MC optimizations to improve power and performance. Notwithstanding, this study focused on proposing a dynamic technique that allows to explore the lower utilization of transaction queues in scalable optical and RF memory interfaces.

In the report by Jeong et al. [17] a Quality of Service (QoS) mechanism to track progress of GPU workload is proposed in order to dynamically adapt the priority of CPU and GPU utilization. The report by Usui et al.[18] extends Jeong's approach [17] to general hardware accelerators trading off not only QoS bandwidth but also latency of applications. Differently of the GPU or CPU priority - focus of these QoS reports - in this study, we approach to dynamically adapt the transaction queue size to match the application.

Janz et al. [19] report employs a software scheduling software framework where through the interaction of the operating system with the application, memory address space dynamic footprint utilization is determined. Our technique is a hardware technique that could be orthogonally coupled to Janz' technique and also collaborate to determine the memory footprint utilization of the system in terms of transaction queue size.

Since the adopted approach is focused on transaction queues, it is orthogonal to optical or RF-based solutions, and therefore, applicable to these systems. The strategy here proposed is also suitable to commercial systems such as HMC [9] with medium degree of MC scalability. Additionally, transaction queue occupation is decreased in RFIop [7] as MCs are scaled. This observation is a motivation to further explore the behavior of shallower transaction queues in this research.

Memscale [20] is a set of software (operating system policies) and specific hardware power mecha-

nisms that enable the trade-off between memory energy and performance in typical memory systems. It dynamically changes voltage and frequency scaling (DVFS) in terms of memory ranks and memory channels. Moreover, it is guided by OS performance counters that periodically monitor memory bandwidth usage, energy utilization, and the degree of performance degradation in the case of trade-off. The proposed approach is orthogonal to Memscale, since the impact on the reduction of transaction queues in terms of power and bandwidth is dynamically explored, which can be triggered by Memscale techniques. What we propose is also orthogonal to the report by Marino [21] since we do not explore transaction queue FS, instead the focus is on saving energy by having dynamic number of buffers adaptable to the memory demand.

Multiscale [22] technique relies on the approach that estimates the bandwidth of each MC independently and selects an appropriate frequency/voltage to maximize energy savings while individually maximize the performance of each application. In this proposed research, we aim to employ the lower utilization of transaction queues through the use of a dynamic strategy that automatically fits the number of entries to the application bandwidth demands. Similar to Memscale, this proposed technique can be coupled to Multiscale due to their orthogonality.

Howard *et al.* [23] proposed memory DVFS to address memory power at data centers using bandwidth as a restricting factor. Although the proposed approach is orthogonal to this study, given that we focus on evaluating the benefits of shallower transaction queues, a combined approach DVFS applied to the transaction queue is an issue for further investigation.

In [24], it was proposed an architecture of servers with mobile memory systems for lower energy-per-bit consumption and efficient idle modes to approach different energy utilization under different bandwidth demands, which can be applied in servers with mobile systems that present larger number of MCs. As part of this research, it is shown the use of mobile memories with new circuitry to reduce power. In addition, orthogonal to the study presented in [24], we focused on the effects of using shallower transaction queues.

Scale-Out Non Uniform Memory Access (NUMA) is an architecture, programming model, and communication protocol that implements a remote direct memory access (RDMA) via using a remote memory controller (RMC) in a traditional NUMA memory [25]. In this proposed approach, we use RF-technology that enables low latencies

even for MCs located in remote positions from the processor whilst have significant lower levels of latency. It can potentially explore remote locations that shows higher latencies and a strategy is proposed in this research that will further lower their utilization.

Zhang *et al.* [26] proposes the utilization of a variation-aware MC scheme that explores the utilization of memory chunks within different access times. The approach proposed in this work is similar, since it explores lower bandwidth utilization of transaction queue. Nevertheless, frequency scaling is one of the main techniques explored in [26], and lowering the number of transaction queues is explored to match the demands on the bandwidth.

ArchShield [27] is an architectural framework that employs runtime testing to identify faulty DRAM cells. Similar to ArchShield that exposes errors at architecture level, our region-based approach can potentially tolerate regions with faulty DRAM cells. Rather than focusing on banks and internal cell levels to approach error-tolerance, the approach proposed in this work is focused on the rank and MC levels, where the performance and energy implications of regions formed by sets of cores and different number of MCs/ranks, given that latter one represent different degrees of memory parallelism. Similar to ArchShield [27], Taassori *et al.* [28] proposed an adaptive MC that retains information of each individual bank, in which DVFS is gradually applied and seeks to find the point of failure (clock synchronization) in these banks. Intersecting with Taassori *et al.* is the granularity at the memory element level, where differences in fabrication variation are utilized to exploit FS independently at each different memory element. Lower utilization of transaction queues of MCs is explored to satisfy different bandwidth demands in this investigation.

Bandwidth effects of increasing the number of MCs in traditional digital-based embedded systems is presented in [16], restricted due to high I/O pin usage. One of the effects observed was the lower utilization of transaction queues, where the proposed approach focuses using transaction queues with dynamic sizes that match the bandwidth demands.

The effects of shallower transaction queues is discussed in [5], where the number of MCs is increased, concurrently the occupation of the queues is lowered. As consequence, many entries are not utilized. To further approach the utilization of these queues, the proposed research matches the current bandwidth via a dynamic approach.

4. Dynamic Transaction Queues Size Mechanism

Before we describe the dynamic transaction queue mechanism, we illustrate first the general operation of transaction queues.

```

while (there are incoming memory transactions)
do
  if (check MTQS) then
    activate_entry(tqc); increment tqc;
  end
end
while (there are memory transactions to be removed) do
  if (tqc >= 0) then
    de-activate_entry(tqc); decrement tqc;
  end
end

```

Algorithm 1: Dynamic transaction queue size mechanism algorithm: *tqc* is assumed starting with 0

4.1. Transaction Queue operation

The transaction queue is typically involved when one cache request is received from the cache system and transformed next into a memory request in the TE (MC), as previously described. In scalable memory systems, typical transaction queue sizes are in the range of 16-32 entries [5], and one memory request occupies one entry in the transaction queue. While the memory is still processing this request, this entry is kept occupied. Transaction queues store cache requests and transform into memory requests are queued due to speed difference between caches and DRAMs.

After processing the request, the entry correspondent to the stored memory request is freed from the transaction queue. Given that transaction queue entries correspond to the maximum transaction queue size, all queue entries are free, since no memory requests are on the way nor requests being processed.

The description of boundaries follow next, and given that the transaction queue size has a maximum limit size, transactions are stored in as long as there are entries available. In case not, all cache requests to that transaction queue are stalled, observing that if these caches can request from other transaction queues other than the latter where the cache request is stored, this request is saved to it/their miss status handling register (MSHR). In this case, all entries are filled with memory requests waiting to be processed. After the current transaction processing is

completed, the correspondent transaction queue entry is released and the number of available entries is further incremented by one.

4.2. Mechanism

In order to improve the sub-utilization of transaction queues [5], a dynamic transaction queue size mechanism is proposed. Since this algorithm 1 being proposed is aimed to be implemented in hardware, it should be of smallest complexity overhead, mainly consisted of simple operations such as activation/deactivation of entries that indirectly control transaction queue size. To implement this mechanism, it is proposed:

- add a counter (transaction queue counter or *tqc*), to represent the number of entries utilized in the transaction;
- novel design of a queue that has several entries is considered instead of using a traditional transaction queue: it will control the activation/deactivation of each of active entries, due to power saving issues.

[Figure 4 about here.]

The hardware kernel of the proposed mechanism should control the number of entries available, depending on the current number of transactions stored in the TE transaction queue. As one new transaction incomes to the transaction queue and there are entries available, the transaction is stored in the queue and concurrently the transaction entry is occupied with this respective memory request. Once checked the availability of entries, whether maximum transaction queue size or *MTQS* has achieved or not, the dynamic transaction queue mechanism performs the correspondent hardware adjustment: *tqc* is incremented by one and one more entry is activated (*activate_entry*) next. In comparison to the traditional queue mechanism where all entries are activated even not used, only used entries are activated and no idle entries in this case.

In similar way, the correspondent entry is removed from the transaction queue after the transaction is processed. Dynamic transaction queue mechanism performs the adjustment of the transaction queue size: the correspondent entry is de-activated (*de - activate_entry*) and *tqc* is decremented by one. Different than the traditional queue mechanism where all entries are activated even if not used, only used entries are active and no idle entries in this case.

The operations of checking the transaction queue size (*check MTQS*) and verification of entries to be

processed both can be implemented using circuits. The circuits needed to implement the dynamic transaction queue mechanism are straightforward comparator circuits and counters. The complexity of the circuits involved in this mechanism is not high in terms of overall processor/memory circuits complexity. Yet, not likely to impact power utilization. Therefore, if these circuits need to be scaled to 32 or even 64 entries, the area and power utilized are still neglectable.

The transaction queue implementation itself can be done through a shift-register element. That is, as a new entry is stored, the shift-register and transaction counter are properly clocked to respectively store the entry and then count it. The activation and deactivation of entries are assumed to be implemented through coupling power-gating inputs to the entries, which allows them to be enabled or disabled whenever a number or no entries are necessary.

Since the number of active entries is significant lower than the maximum [5], power benefits can be noticed as further described in Section 5.

[Table 1 about here.]

5. Experimental Results

In this section, experiments were executed to demonstrate the power and performance effects, with different transaction queue sizes in scalable memory systems.

5.1. Methodology

To have a global picture of the methodology applied in this research, we list simulators considered and corresponding description of their characteristics, available in Table 1. The methodology employed to obtain bandwidth is adopted based on [29]. That is, by using bandwidth-bound benchmarks to stress the memory system, M5 [30] and DRAMsim [31] simulators were combined.

To evaluate the scalable memory system as designed, data from detailed accurate simulators following the methodology developed in [29] were combined, as described in Table 1. As to explore the scalability of future multicore generations, a 32-multicore processor (larger than current server processors (e.g. [32]) with 32 MCs was selected to represent scalable memory systems (significant larger number of MCs than current processors (e.g. [32])). A 32-multicore model was created in M5 [30], based upon benchmark execution generates memory transactions that are then captured by DRAMsim [31] properly configured with 32 RFMCs, so that core:

MC ratio is homogeneous, i.e., 32:32. DRAMsim responds to M5 with the result of each memory transaction concurrently in the sequence. In this way, each RFMC is assumed to be connected to one single rank to extract its maximum bandwidth.

To evaluate the dynamic behavior, its behavior is compared to the behavior of other transaction queue sizes (from 1 to 16 entries) obtained via static design space exploration, taking into consideration bandwidth and rank-energy-per-bit utilization. The baseline configuration presents 32 RFMCs and 16 transaction queue elements.

[Table 2 about here.]

We employ a 4.0GHz (Alpha ISA) and 4-wide out-of-order (OOO) core, with RFMCs at 2.0GHz (typically at half of microprocessor clock frequency [32]). Cacti [33] is chosen to acquire cache latencies and adopt MSHR counts of typical microprocessors [34]. L2 caches at 1 MB/core are interconnected via an 80GB/s-RF-crossbar with 1-cycle latency are adopted. This magnitude was designed so that when ranks and MCs are scaled, it does not restrict the total throughput. Same timing settings adopted as those presented in [35][36]. RF-crossbar was set with a single cycle latency, adopted the same timing settings as in [4]. That is, 200ps for TX-RX delays plus the rest of the burst cycle used to transfer 64 Bytes (memory word) using high speed and modulation.

Observing the RF-crossbar upper constraint, we have selected a medium data-rate DDR3-rank employed in typical PCs (64 data bits, based on the DDR3 model Micron MT41K128M8 of 1GB [37], and listed in Table 2a). All architectural parameters are summarized in Table 2a.

To model RF communication, RF-circuitry modeling and scaling took into consideration those proposed in [35][38][36][39]. In these models, crosstalk effects, modulation, interference, and noise margin reduction are employed aiming at low bit error rate (BER). Moreover, these models are validated with prototypes for different transmission lines [40][38], following ITRS [41]. RF-interconnection power is derived as in [2]; that is, using McPAT [6] tool at different frequencies to determine FE/TE power components and RF-interconnection power modeling as in [4].

To determine the total energy-per-bit spent, DRAMsim power infrastructure is employed and then combine it to the memory throughput, as extracted from M5 statistics (ratio of the number of memory transactions and execution time).

[Figure 5 about here.]

By adopting methodology similar to the one proposed to evaluate the memory system [34], bandwidth-bound benchmarks with a medium-to-significant number of misses per kilo-instructions (MPKI) were selected, taking into consideration the following aspects:

- Guarantee proper calibration by having each rank bandwidth saturated. In all benchmarks, more than one entry is present at each transaction queue of each MC, what guarantees that bandwidth in each rank is saturated.
- The selected input sizes are a trade-off between simulation times and memory traffic generated.
- In high scalable memory systems, typically at least 16 entries per transaction queue are utilized [4][7][2]. Thus, the baseline reference of the results presented is the 16-entry one (transaction queue with 16 entries).

In order to evaluate this scalable memory system, we have selected seven bandwidth-bound benchmarks: (i) STREAM suite [12], composed of ADD, COPY, SCALE and TRIAD benchmarks, (ii) pChase [13] with pointer chase sequences randomly accessed, (iii) Multigrid (MG), Scalar Pentadiagonal (SP), Fast Fourier Transform (FFT) from NPB benchmarks [42], and SOR method (black and red matrices) [43]. All benchmarks are set to make use 32 threads, since we are employing a 32-core processor. No special thread-to-core mapping is applied when executing these benchmarks. Table 2b lists the benchmarks experimented, input sizes, read-to-write rate, and L2 MPKI obtained from experiments. In all benchmarks, parallel regions of interest are executed until completion, and input sizes guarantee that all memory space used is evaluated. Average results are calculated based on harmonic average.

5.2. Experimental Results

In this section, we present the results regarding to the aspects of memory bandwidth and rank energy-per-bit magnitude. Since all STREAM benchmarks belong to the same STREAM suite, instead of presenting four benchmarks they are presented altogether as STREAM.

The dynamic transaction queue size resultant on all the experiments (bandwidth, instructions per cycle - IPC, and energy) are marked. The algorithm resultant size is between 2 to 4 entries for MG and SP whilst it goes from 4 to 8 entries for STREAM and pChase. Different dynamic size obtained is due to different bandwidth demands of the benchmarks

evaluated. As result, the algorithm allows the utilization of lower number of entries when compared to 16 entries, which corresponds to the baseline - as previously described and used in scalable memory systems [7][2].

Figure 5a illustrates experimental results on bandwidth. The dynamic version presents an expected bandwidth magnitude, i.e., with magnitude levels within the 16-1 range entry, the latter ones obtained with experiments of individual sizes. As expected, since the dynamic transaction queue tries to optimize the utilization of the transaction queue and employs less elements than the total size (16 elements, set as baseline as discussed previously), bandwidth levels are lower than the baseline yet better than small sizes, e.g., 2-4 or 4-8 entries. For STREAM and FFT, dynamic version present higher bandwidth than the 4-entry version. For the remaining benchmarks it presents 2 to 8% less bandwidth, which is a yet open trade-off for having lower transaction queue size (and power reduction at the MC).

The point where bandwidth starts to be significantly reduced happens with 4 transaction queue sizes [5]. Indeed, this point corresponds to the dynamic approach matching the bandwidth needs, given the number of entries available, memory behavior of the benchmark, cache L2 MSHRs, and/or number of outstanding memory transactions.

Before the discussing rank energy-per-bit levels, processor performance impact (in terms of IPC) is shown in Figure 5b. IPCs generally follow the behavior of bandwidth as previously described. Most interestingly, it is noted that the IPC magnitude level for the obtained through dynamic transaction queue algorithm is less than the one obtained when bandwidth is comparatively measured. Therefore, in spite of using bandwidth, IPC/bandwidth trade-off could be considered to trigger the algorithm.

It is illustrated the related rank energy-per-bit results in Figure 6. The dynamic version present similar rank energy-per-bit levels to the 4-entry system, except for STREAM where levels are larger than 4- and 8-entry. Similar to the 4-entry version, the dynamic transaction queue version presents lower energy-per-bit levels than for 1-2 entries. Analyzing the simulator output statistics, it is believed that such event happens due to random behavior settings of pChase. We observe different energy-per-bit magnitudes from [5], since we believe the latter calculated and compared The general behavior which is energy-per-bit levels to proportionally increase with lower transaction-queue size is expected since lower transaction queues are likely to present lower bandwidth, and higher latency, i.e., longer times and therefore

higher energy utilization.

By combining energy and bandwidth aspects, if such a trade-off bandwidth drop of about 25% is acceptable, this implies that 50% to 75% of transaction queue entries are not be used, what lead to significant transaction queue power savings. In this case, as observed in the sequence, rank energy-per-bit can be saved of about 20% whilst using less amount of transaction queue positions and saving power.

[Figure 6 about here.]

To summarize, it is shown interesting trade-offs of dynamic configurations in terms of bandwidth/performance and energy while employing less amount of elements, by comparing Figures 5a, 5b and 6. It is able to observe that is possible to have equivalent performance to 16 entries while presenting potential energy-per-bit saving with 4 and 8 entries, less than 50% of the total number of entries.

Importantly, we do not show the dynamic transaction queue energy utilization. However, as a result of the target technique, given that the bandwidth and IPC results of the dynamic queue are similar to the 4-entry system, the energy utilization is likely to follow this behavior: if compared to the 16-entry baseline is likely to use 4x more energy. So a trade-off memory energy utilization versus transaction queue utilization should be explored to clarify this behavior, which We leave as a further investigation. aspect as a future investigation.

6. Conclusions and Future Plans

One of consequences on employing scalable memory interfaces that has larger number of MCs is the decrease on the number of entries utilized in transaction queues. In this paper, we have proposed a mechanism that dynamically matches the number of entries utilized to the number of entries demanded by programs. Evaluations on the bandwidth and impact of power when performing dynamic transaction queue size implementation in the context of scalable memory systems are done.

Experimental results obtained show that, by adopting a transaction queue with dynamic size that matches the number of transactions to the behavior of applications. A trade-off of saving up to 75% of the transaction queue entries causes bandwidth drop and rank energy-per-bit increase. The utilization of a lower amount of entries is likely to save area at the MCs, with the expense of a lower bandwidth and higher utilization of memory energy. The combination of lower number of MCs to lower entries or

higher number of MCs to higher number of entries are likely solutions to be further investigated.

Moreover, the dynamic solution trade-off performance and energy losses are small if compared to 4-to-16 entries. A further investigation is required to expand the boundaries of the trade-off.

As future directions, we aim to investigate variations of the dynamic approach that includes processor utilization and others [20][21] that take into consideration factors as bandwidth solely. Methods that combine DVFS [23], temperature, processor to memory locality (important to distributed memory systems) and other memory traffic patterns are listed as directions to be considered.

Similar investigation would be interesting to be applied on the context of BD clusters with embedded systems' features [44] with detailed design choices and optimizations are performed by decomposing the global system into a set of simple [45] and well-described components. Modelling methodologies based on data analysis that characterizes the performance of embedded applications are applied to support system-level designers to predict the number of execution cycles on a embedded processor [46]. As basis of a high-level characterisation on the software functionality and hardware architecture, we aim further to include the findings of this methodology in system research studies.

7. Compliance with Ethical Standards:

(In case of Funding) Funding: This study was funded by X (grant number X).

Conflict of Interest: Author A has received research grants from Company A. Author B has received a speaker honorarium from Company X and owns stock in Company Y. Author C is a member of committee Z. OR if no conflict exists: Author A declares that he/she has no conflict of interest. Author B declares that he/she has no conflict of interest.

(In case animals were involved) Ethical approval : All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

(And/or in case humans were involved) Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

(If articles do not contain studies with human participants or animals by any of the authors, please

select one of the following statements) Ethical approval: This article does not contain any studies with human participants performed by any of the authors. (Or) Ethical approval: This article does not contain any studies with animals performed by any of the authors. (Or) Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

(In case humans are involved) Informed consent: Informed consent was obtained from all individual participants included in the study.

8. Bibliography

- [1] LPDDR4 Moves Mobile, mobile Forum 2013, presented by Daniel Skinner, Accessed date: 01/27/2016; http://www.jedec.org/sites/.../D_Skinner_Mobile_Forum_May_2013_0.pdf.
- [2] Marino, M. D., RFIof: An RF approach to the I/O-pin and Memory Controller Scalability for Off-chip Memories, in: CF, May 14-16, Ischia, Italy, ACM, 2013, pp. 100–110.
- [3] D. Vantrease et al, Corona: System Implications of Emerging Nanophotonic Technology, in: ISCA, IEEE, DC, USA, 2008, pp. 153–164.
- [4] Therdsteeerasukdi, Kanit et al., The DIMM tree architecture: A high bandwidth and scalable memory system, in: ICCD, IEEE, 2011, pp. 388–395.
- [5] Marino, M.D; Li K.C., Implications of Shallow Memory Controller Transaction Queues in Scalable Memory Systems, Journal of Supercomputing.
- [6] Sheng Li et al, McPAT: an integrated power, area, and timing modeling framework for multicore and manycore architectures, in: MICRO'09, ACM, New York, USA, 2009, pp. 469–480.
- [7] Marino, M. D., RFIof: RF-Memory Path To Address On-package I/O Pad And Memory Controller Scalability, in: ICCD, 2012, Montreal, Quebec, Canada, IEEE, 2012, pp. 183–188.
- [8] Little, J. D. C. (1961). "A Proof for the Queuing Formula: $L = W$ ". Operations Research 9 (3): 383387., accessed date: 11/08/2016 ; <http://dx.doi.org/10.1287/opre.9.3.383>.

- [9] Hybrid Memory Cube Specification 1.0, accessed date: 09/12/2016 ; <http://www.hybridmemorycube.org/>.
- [10] JEDEC Publishes Breakthrough Standard for Wide I/O Mobile DRAM, accessed date: 11/03/2016 ; <http://www.jedec.org/>.
- [11] Aniruddha N. Udip, Designing Efficient Memory for Future Computing Systems , in: PhD Thesis, University of Utah, School of Computing, Utah, USA, 2012, pp. 1–126.
- [12] McCalpin, J. D., Memory Bandwidth and Machine Balance in Current High Performance Computers, IEEE TCCA Newsletter (1995) 19–25.
- [13] The pChase Memory Benchmark Page, accessed date: 10/05/2016 ; <http://pchase.org/>.
- [14] Bruno Nogueira et al., Multi-objective optimization of multimedia embedded systems using genetic algorithms and stochastic simulation, *Soft Computing*.
- [15] Darren M. Chitty, Improving the performance GPU-based genetic programming through exploitation of on-chip memory, *Soft Computing* 20 (2) (2016) 661–680.
- [16] Marino, M. D., Li, K.C., Insights on Memory Controller Scaling in Multi-core Embedded Systems , *International Journal of Embedded Systems* 6 (4).
- [17] M. K. e. a. Jeong, A qos-aware memory controller for dynamically balancing gpu and cpu bandwidth use in an mp soc, in: DAC, ACM, New York USA, 2012, pp. 850–855.
- [18] SQUASH: Simple QoS-Aware High-Performance Memory Scheduler for Heterogeneous Systems with Hardware Accelerators, accessed date: 10/02/2016 ; <http://http://arxiv.org/abs/1505.07502>.
- [19] J. M. R. et al., A framework for application guidance in virtual memory systems, in: VEE, ACM, 2013, pp. 344–355.
- [20] Deng, Q. et al., Memscale: active low-power modes for main memory, in: Proceedings of the Sixteenth ASPLOS, ACM, New York, NY, USA, 2011, pp. 225–238.
- [21] Marino, M.D., ABaT-FS: Towards adjustable bandwidth and temperature via frequency scaling in scalable memory systems, *Microprocessors and Microsystems*.
- [22] Deng, Q. et al., Multiscale: Memory system dvfs with multiple memory controllers, in: Proceedings of the 2012 ACM/IEEE International Symposium on Low Power Electronics and Design, ISLPED '12, ACM, New York, NY, USA, 2012, pp. 297–302.
- [23] David et al., Memory Power Management via Dynamic Voltage/Frequency Scaling, in: Proceedings of the 8th ACM International Conference on Autonomic Computing, ICAC '11, ACM, New York, NY, USA, 2011, pp. 31–40.
- [24] Malladi et al, Towards Energy-proportional Datacenter Memory with Mobile DRAM, in: Proceedings of the 39th Annual International Symposium on Computer Architecture, ISCA '12, IEEE Computer Society, Washington, DC, USA, 2012, pp. 37–48.
- [25] Novakovic, Stanko et al., Scale-out NUMA, in: Proceedings of the 19th International Conference on Architectural Support for Programming Languages and Operating Systems, ASPLOS '14, ACM, New York, NY, USA, 2014, pp. 3–18.
- [26] Zhang, Xianwei et al., Exploiting dram restore time variations in deep sub-micron scaling, in: Proceedings of the 2015 Design, Automation & Test in Europe Conference & Exhibition, DATE '15, San Jose, CA, USA, 2015, pp. 477–482.
- [27] Nair, Prashant J. et al., ArchShield: Architectural Framework for Assisting DRAM Scaling by Tolerating High Error Rates, in: Proceedings of the 40th Annual International Symposium on Computer Architecture, ISCA '13, ACM, New York, NY, USA, 2013, pp. 72–83.
- [28] Taassori M. et al., Exploring a Brink-of-Failure Memory Controller to Design an Approximate Memory System, in: 1st Workshop on Approximate Computing Across the System Stack (WACAS), ACM, Salt Lake City, 2014, pp. –.
- [29] Marino, M. D., On-Package Scalability of RF and Inductive Memory Controllers, in: *Euromicro DSD*, IEEE, 2012, pp. 923–930.
- [30] Nathan L. Binkert et al, The M5 Simulator: Modeling Networked Systems, *IEEE Micro* 26 (4) (2006) 52–60.
- [31] David Wang et al, DRAMsim: a memory system simulator, *SIGARCH Comput. Archit. News* 33 (4) (2005) 100–107.

- [32] AMD Reveals Details About Bulldozer Microprocessors, accessed date: 09/06/2016 - http://www.xbitlabs.com/news/cpu/display/20100824154814_AMD_Unveils_Details_About_Bulldozer_Microprocessors.html (2011).
- [33] CACTI 5.1, accessed Date: 10/22/2016; <http://www.hpl.hp.com/techreports/2008/HPL-200820.html>.
- [34] Loh, Gabriel H., 3D-Stacked Memory Architectures for Multi-core Processors, in: ISCA, IEEE, DC, USA, 2008, pp. 453–464.
- [35] M. Frank Chang et al, CMP Network-on-Chip Overlaid With Multi-Band RF-interconnect, in: HPCA, 2008, pp. 191–202.
- [36] M.C.F. Chang et al., Power reduction of CMP communication networks via RF-interconnects, in: MICRO, IEEE, Washington, USA, 2008, pp. 376–387.
- [37] Micron manufactures DRAM components and modules and NAND Flash, accessed date: 01/08/2016 ; <http://www.micron.com/>.
- [38] M.C.F. Chang et al, Advanced RF/Baseband Interconnect Schemes for Inter- and Intra-ULSI Communications, IEEE Transactions of Electron Devices 52 (2005) 1271–1285.
- [39] Sai-Wang Tam et al, RF-Interconnect for Future Network-on-Chip, Low Power Network-on-Chip (2011) 255–280.
- [40] G. Byun et al, An 8.4Gb/s 2.5pJ/b Mobile Memory I/O Interface Using Bi-directional and Simultaneous Dual (Base+RF)-Band Signaling, in: ISSCC, IEEE, 2011, pp. 488,490.
- [41] ITRS HOME, accessed date: 08/18/2016 ; <http://www.itrs.net/>.
- [42] NAS Parallel Benchmarks, accessed date: 08/09/2016; <http://www.nas.nasa.gov/Resources/Software/npb.html/>.
- [43] R. G. Rauber T., Parallel programming: for multicore and cluster systems, 2nd Edition, Springer, 2013.
- [44] Marino, M.D; Li K.C., Last level cache size heterogeneity in embedded systems, Journal of Supercomputing 72 (2) (2016) 503–544.
- [45] Marino, M.D, L2-Cache Hierarchical Organizations for Multi-core Architectures, in: Frontiers of High Performance Computing and Networking – ISPA 2006 Workshops: ISPA 2006 International Workshops, FHPCN, XHPC, S-GRACE, GridGIS, HPC-GTP, PDCE, ParDM-Com, WOMP, ISDF, and UPWN, Proceedings, Springer, 2006, pp. 74–83.
- [46] G. Bontempi , W. Kruijtzter, The use of intelligent data analysis techniques for system-level design: a software estimation example, Soft Computing 8 (7) (2004) 477–490.
- [47] Calculating Memory System Power for DDR3 Introduction, accessed date: 12/06/2015 ; <http://www.micron.com/>.

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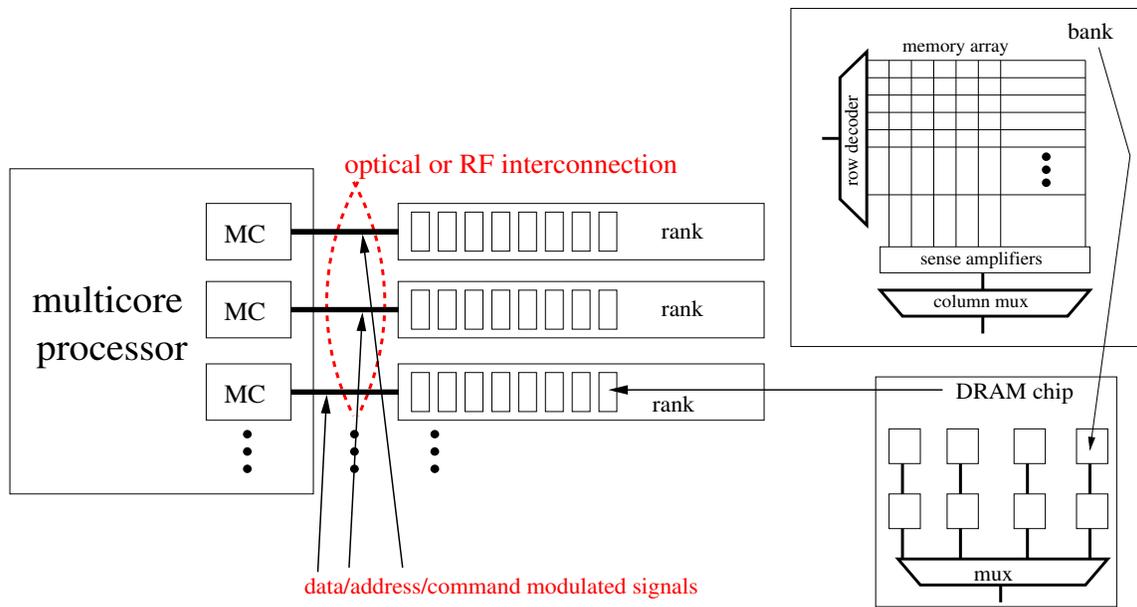


Figure 1: memory system general overview

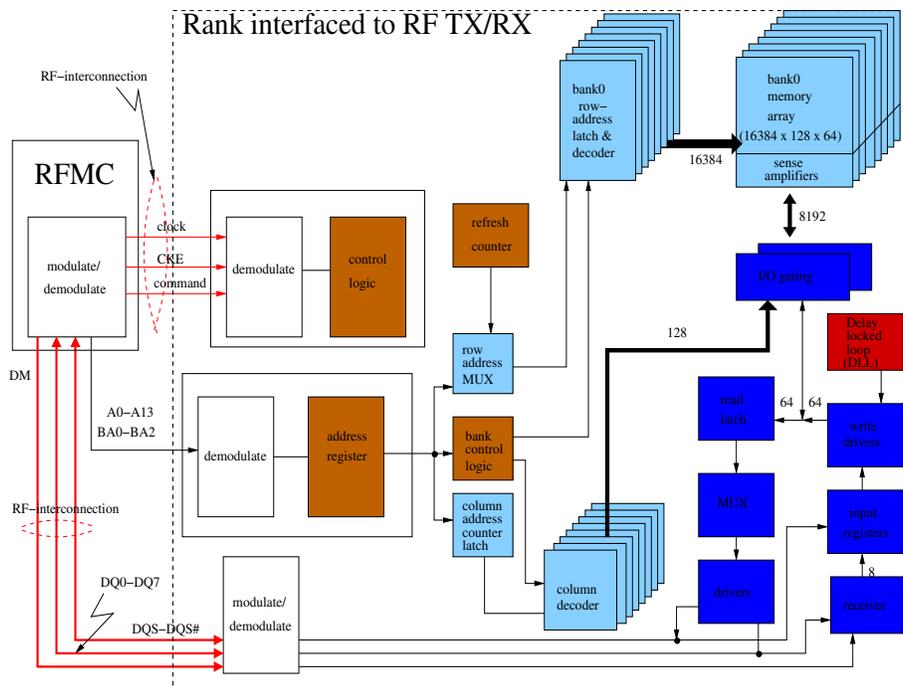


Figure 2: (16384 rows, 128 columns, 64 data bits) rank interfaced to a RF-based MC; based on [2][47]

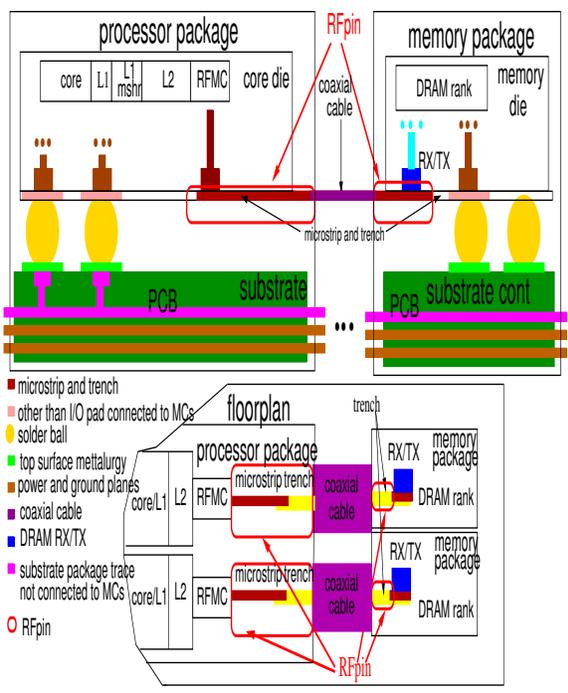
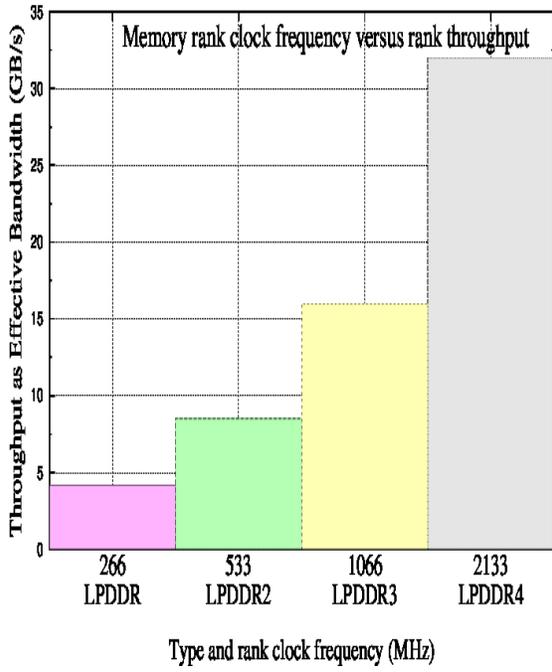


Figure 3: left to right: (a) frequency versus bandwidth, repeated from [1]; (b) RFiof, repeated from [2]

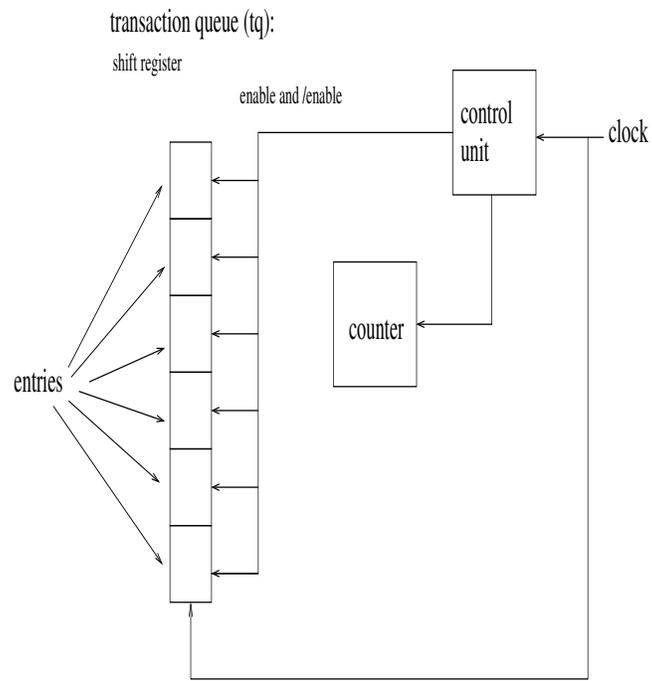


Figure 4: transaction queue circuits

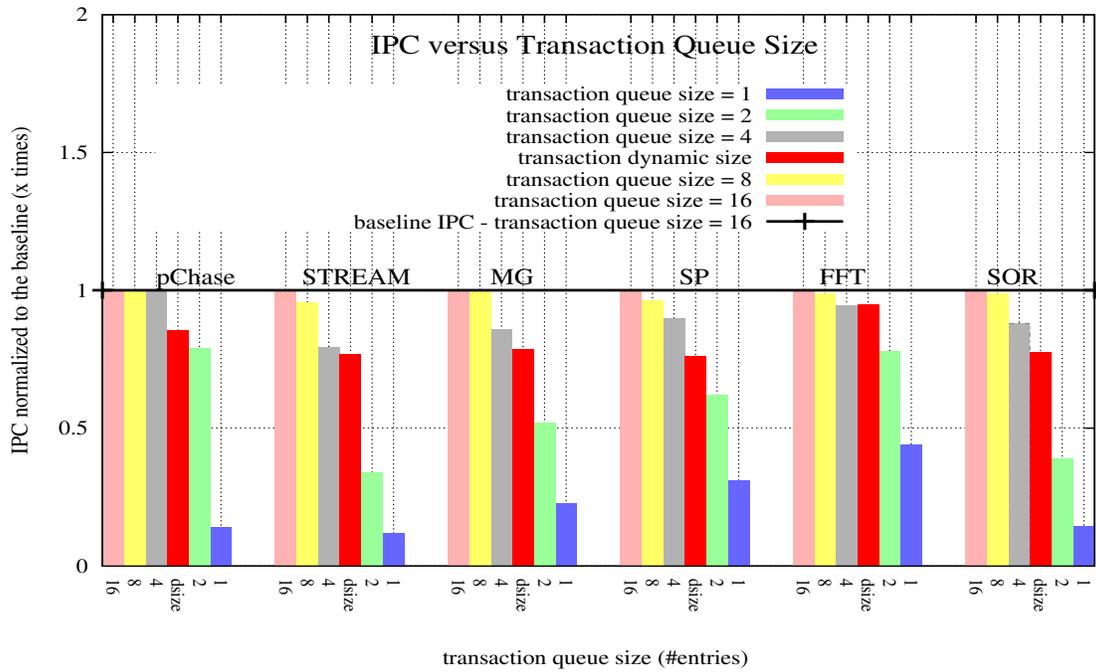
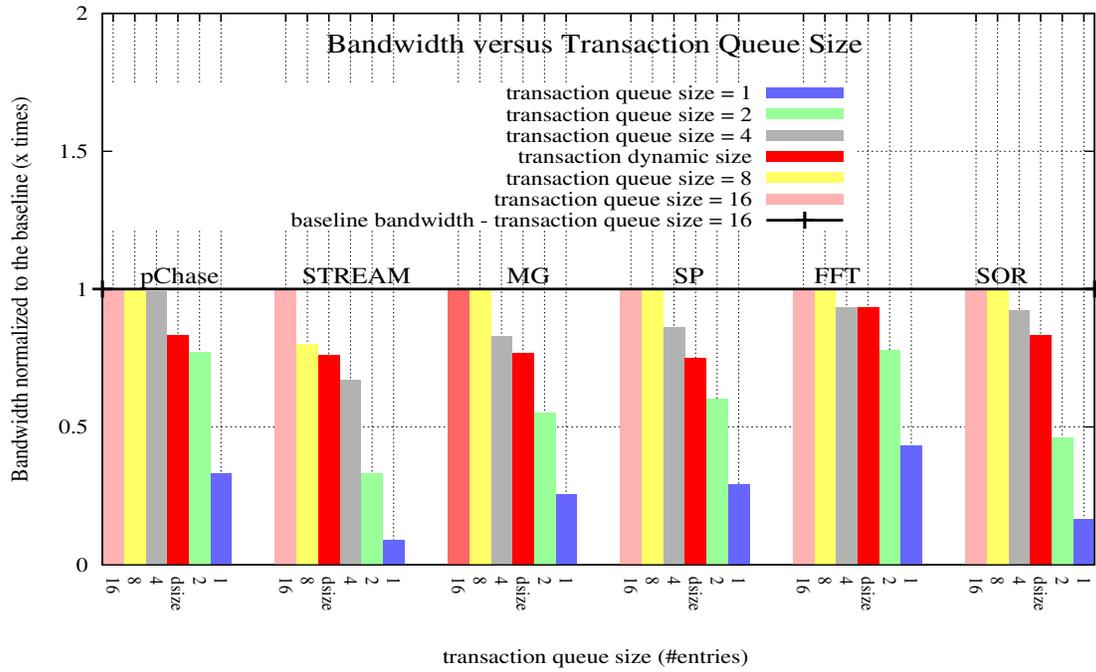


Figure 5: a and b: top to bottom, bandwidth and instructions-per-cycle (IPC) for STREAM, pChase, MG, SP, FFT and SOR

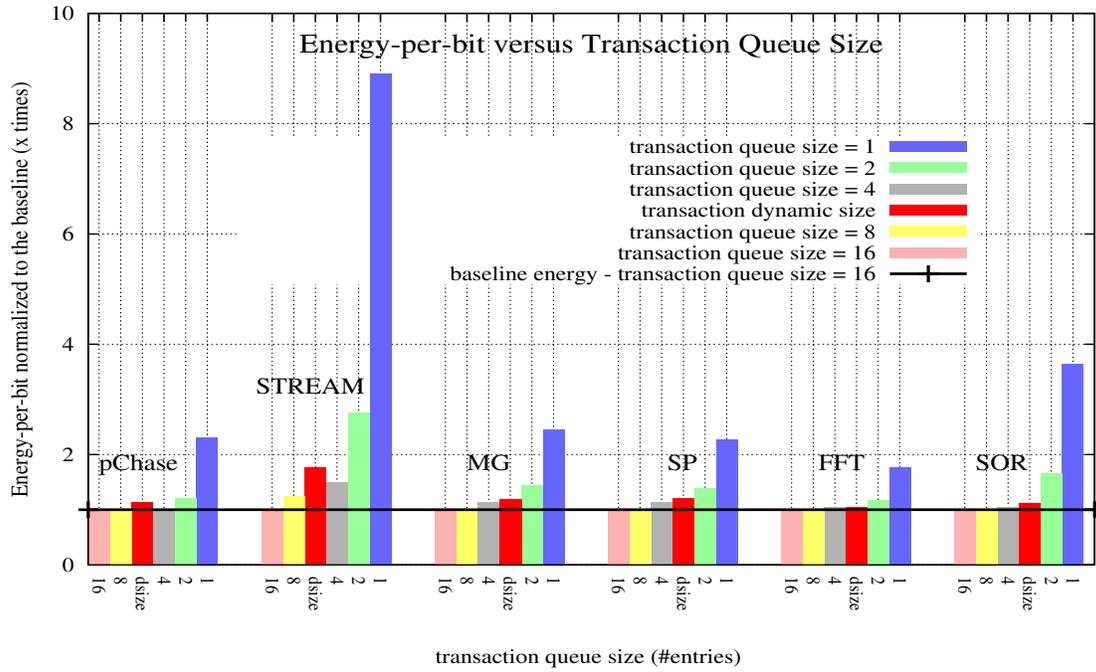


Figure 6: energy versus transaction queue size for STREAM, pChase, MG and SP

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tool	description
Cacti [33]	cache latencies configured with
McPAT [6]	determine power of individual path elements: TE and FE
DRAMsim [31]	Capture memory transactions from M5 configured with 32 RFMCs. Respond to M5 with the result of the memory transaction. Determine power spent and the number of memory accesses and [31][37]. transaction queue size.
M5 [30]	Configured as 32-core OOO processor and not L2 shared cluster (avoid sharing). Generates memory transactions which are passed to DRAMsim [31]. Miss-status handling register (MSHR) counts from typical microprocessors [34].
RF-crossbar	Implemented in M5 [30] with RF settings from [35][36].
RF-communication delays	RF-circuitry modeling and scaling [35][38].

Table 1: methodology: tools and description

Core	4.0 GHz, OOO, multicore, 32 cores, 4-wide issue, tournament branch predictor
Technology	22 nm
L1 cache	32kB dcache + 32 kB icache; associativity = 2 MSHR = 8, latency = 0.25 ns
L2 cache	1MB/per core ; associativity = 8 MSHR = 16; latency = 2.5 ns
RF-crossbar	latency = 1 cycle, 80GB/s
RFMC trans. queue	32 RFMCs; 1 RFMC/core, 2.0GHz, on-chip entries = 16/MC, close page mode
Memory rank	DDR3 1333MT/s, 1 rank/MC, 1GB, 8 banks, 16384 rows, 1024 columns, 64 bits, Micron MT41K128M8 [37], tras=26.7cycles, tcas=trcd=8cycles
RF interconnection length size delay	2.5 cm 0.185ns

Benchmark	Input Size	read : write	MPKI
Copy, Add, Scale, Triad (STREAM)	4Mdoubles per core 2 iterations	2.54:1	54.3
pChase	64MB/thread, 3 iterations, random	158:1	116.7
Multigrid:MG (NPB)	Class B 2 iterations	76:1	16.9
Scalar Pentadiagonal: SP (NPB)	Class B 2 iterations	1.9:1	11.1
FFT: Fast Fourier Transform (NPB) (NPB)	Class B, 3 iterations	1.3:1	6.8
SOR	6000 x 6000, 3 iter.	2.5:1	12.5

Table 2: a and b: methodology tools description; benchmarks description