International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 11s
DOI: https://doi.org/10.17762/ijritcc.v11i11s.8169
***Article Received:** 26 June 2023 **Revised:** 22 August 2023 **Accepted:** 08 September 2023*

A Research to Improve Contiguous Memory Allocation in Linux Kernel

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Abstract—The demand for Contiguous Memory Allocation (CMA) has witnessed significant growth in both low-end and high-end devices in recent years. However, the existing practices for utilizing CMA prove insufficient, particularly when catering to the needs of low-end (32-bit) devices. CMA, a Linux program used for memory reservation and allocation, faces limitations in its current implementations. Presently, techniques such as Scatter-Gather Direct Memory Access (DMA), Input Output Memory Management Unit (IOMMU), and Memory Reservation are commonly employed for contiguous memory allocation. Unfortunately, these methods are financially impractical for low-end devices and struggle to efficiently allocate substantial memory chunks, leading to latency concerns. In this paper, we introduce an improved CMA approach that intelligently allocates virtual memory for data mapping as needed. Alternatively, it directly allocates and deallocates physical memory without the necessity of virtual memory mapping, employing the DMA_KERNEL_NO_MAPPING attribute within the DMA Application Programming Interface (API). By adopting this method, latency is reduced, and the facilitation of larger memory allocations is promoted, addressing the limitations of the current techniques.

Keywords- Contiguous Memory Allocation (CMA), Scatter-Gather Direct Memory Access (DMA), Input Output Memory Management Unit (IOMMU), Memory reservation technique, Latency.

I. INTRODUCTION

Nowadays, the requirement of physical contiguous memory is in extreme demand, specifically for low-end devices (32-bit devices). The currently available techniques like for allocation and deallocation are inadequate. The Scatter-Gather Direct Memory Access (DMA), Input Output Memory Management Unit (IOMMU), Memory Reservation technique/ hardware are the frequently used techniques for contiguous memory allocation. These techniques are very costly for low-end devices. Hence, CMA was introduced for low-end devices. The CMA technique introduced to allocate and deallocate memory big size physical continuous memory blocks and improve latency. There are some 32-bit low-end embedded systems, which requires allocating large size physical memory and can’t afford to embed extra hardware like IOMMU and Scatter Gather DMA due to cost and space limitations. This condition encourages the low-end devices to use CMA. The CMA basically emphasizes on Migration Type and Page block modules.

Regardless of the way that it is extremely advantageous for the memory task, it can limit memory use and waste emphatically. There are a few hardware arrangements for settling this issue, like Scatter-Gather DMA and IOMMU. In any case, the expenses of the extra hardware are fundamentally higher for 32-bit gadgets. CMA is a Linux programming thing fully intent on deciding memory part as well as capable memory use hardships. There are various gadgets on embedded structures that miss the mark on Scatter-Gather DMA or IOMMU office, as well as adjacent memory blocks for identification [1], [2]. They assemble gadgets like cameras, video decoders, encoders, etc. Nevertheless, such gadgets habitually need a lot of memory, bringing about the shortfall of structures. Specific mounted gadgets fuel extra necessities on the supports. They can, for instance, follow up on upholds distributed to a specific memory breaking point or supports doled out to an unequivocal memory bank (expecting somewhere around one memory bank is available in the system). As of late, there has been a gigantic progression in the advancement of introduced contraptions (especially in the V4L locale), and there have been different kinds of drivers that solidify their memory part code. A gigantic piece of them utilizes bootmem-based methodologies[7], [8]. The CMA structure is an exceptional memory structure that associates memory circulation systems. It gives an immediate API to device drivers while being portable and private [9]. This is conceivable because of the constant area, which doesn't hurt confirmed CMA. The CMA puts a solid accentuation on memory. During the boot cycle, it stores a huge memory space for coterminous allocation[10], [11]. If the held memory isn't completely used by the bordering memory, it is available to inferior clients, for example, elective gadgets that don't require coterminous memory; any other way, that memory would be squandered. The adjoining memory part required the pages assigned to inferior clients. At the point when the CMA cycle requires it, it puts together the pages and uses them for adjoining

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memory assignments [12], [13]. The organized block diagram of CMA is as mentioned in Figure 1.

The CMA can store the necessary memory. It will be retained at boot time via the part order line or the contraption tree. In Linux, these pages are listed next to the CMA memory that was stored as being adaptable, durable, locked, etc. The handy pages are _2nd-class clients_ that non-CMA processes can use. The compact pages can be relocated or coordinated off [1][14]-[16] if the adjoining assignment expects them. The CMA uses explicit CMA memory, which is crucial for blended media and non-sight and sound workouts in any case, as shown in Figure 1. At boot time, the CMA stores the memory. Whatever method is used; it can handle the memory task well. Through the organizational structure of DMA, CMA gains. The initial capability of the CMA region was a global memory that was accessible to anyone. CMA has a beginning and an end, and as of right now, each page is designated as either a portable or long-term page. The memory included in this CMA start and end address is accessible to everyone. Different cycles can make use of plain flexible pages. [1] [17]-[20].

To allocate CMA memory using DMA, a close-by memory attributes API could be used. It is distributed from the CMA memory area when CMA memory is referred to using the DMA API. With the preparation of real memory to virtual memory, the portable pages can be moved[1] [12], [13]. As a result, the planned system will probably make use of it. Linux uses virtual memory for every cycle. Figure 1 illustrates the ongoing reservation-based strategy and the CMA-based methodology. The CMA was not fully resolved at startup time. As shown in Figure 1, the system included memory for exchange, mmpaed archives, and flexible memory pages when CMA didn't use this memory region operation.

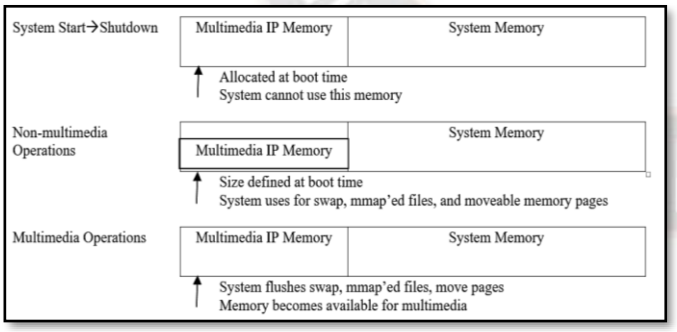
System Start→Shutdown
Multimedia IP Memory
System Memory
Allocated at boot time
System cannot use this memory
Non-multimedia Operations
System Memory
Multimedia IP Memory
Size defined at boot time
System uses for swap, mmap'ed files, and moveable memory pages
Multimedia Operations
Multimedia IP Memory
System Memory
System flushes swap, mmap'ed files, move pages
Memory becomes available for multimedia

Figure 1. Block Diagram of CMA.

The CMA is expected for I/O gadgets that can manage actual memory that is nearby. This wouldn't be a worry on systems with an I/O IOMMU since the IOMMU might course non-abutting memory areas to coterminous bits of genuine memory [1], [24]-[27]. Moreover, a couple of gadgets are equipped for scattering/gathering DMA. All I/O gadgets ought to be equipped for working with an IOMMU or scattering/collecting DMA. Tragically, this isn't true, and a few gadgets need truly coterminous help. A device driver can convey a close-by pad in one of two ways. At startup time, the contraption driver can disperse a lump of actual memory. Since a significant level of the actual RAM would be accessible at boot time, this is dependable. Notwithstanding, if the I/O gadget isn't utilized, the dispensed actual memory is just squandered[1][24], [28],- [30]. Albeit a piece of actual memory can be dispersed upon demand, it could be hard to find a neighboring unfenced of the expected size. The benefit, then again, is that memory might be relegated when required. CMA resolves this particular issue by consolidating the advantages of the two methodologies while killing their drawbacks. The essential idea is to make it possible to move distributed genuine pages to set aside satisfactory room for lining support. More information on how CMA capacities can be found here [1] [19], [27]-30].

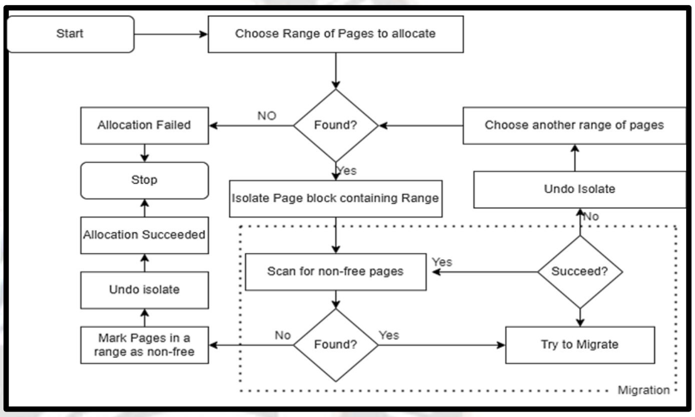

Figure 2. Workflow of Contiguous Memory Allocation System.

Figure 2 illustrates the current work cycle of the CMA in the Linux location and how it tries to relocate and reestablish pages. I) It should be possible to reserve CMA memory when an application requests it from a held CMA location by referring to the amount of memory that will be saved at the time of the request; ii) When a booking request is sent off CMA, it begins selecting the number of pages to assign from the saved CMA district in the hopes that the CMA driver was aware of the application's request for memory. The page block is then isolated from that reach so that no one can use the district simultaneously. If the number of pages isn't detected, the component fails the referenced memory test; iii) Following page block segregation by the CMA driver. Then, it begins searching for blank pages and makes an effort to transfer blank pages or blank pages used by another non-CMA activity; v) If from the constraint block no pages were used by various cycles, mark pages there as free and fix the disengagement of page blocks will follow the delivery of referenced memory [1] [20], [35]- [37]. iii) If from the constraint block no pages were used by various cycles, mark pages there as

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free and fix the disengagement of page blocks until referenced memory can be allotted.

II. LITERATURE REVIEW

A. Contiguous Memory Allocation and Memory Management

Contiguous memory allocation is a critical aspect of modern operating systems, particularly in the context of the Linux kernel. Suryavanshi and Sharma (2022) [1] propose an approach to enhance contiguous memory allocation within the Linux kernel. They review existing strategies, aiming to improve memory utilization and allocation efficiency. Similarly, Park, Kim, and Yeom (2019) [2] introduce GCMA (Guaranteed Contiguous Memory Allocator), which focuses on ensuring contiguous memory allocation for performance-critical tasks. These studies reflect a concerted effort to refine memory allocation techniques in operating systems.

Corbet's articles on five-level page tables [3] shed light on the evolving complexity of memory management in modern systems, while Zeng (2012) [5] delves into the Android ION memory allocator, highlighting its significance in resource management for mobile devices. These references underscore the ongoing research into enhancing memory allocation and management strategies in diverse computing environments.

B. Efficient Virtual Memory and Big Memory Systems

Efficiency in memory management is pivotal for various contexts, including big memory servers and emerging scale-out workloads. Basu et al. (2013) [6] propose techniques for efficient virtual memory management in big memory servers. Their work showcases the importance of tailored memory strategies to optimize resource utilization. Nazarewicz (2012) [7] discusses the contiguous memory allocator, further emphasizing the relevance of effective memory management in modern computing.

Kwon et al. (2016) [15] focus on coordinated and efficient management of huge pages, aligning with the growing demand for optimized memory usage in large-scale systems. These studies highlight the importance of efficient memory allocation strategies to meet the demands of resource-intensive workloads.

C. Dynamic Memory Allocation and Role in Memory Management

Dynamic memory allocation plays a pivotal role in optimizing memory usage. Patil and Irabashetti (2014) [16] emphasize the significance of dynamic memory allocation in memory management, particularly within ad hoc networks. The dynamic allocation approach is integral to adapting to varying workloads and resource requirements.

D. Memory Compression and Advanced Techniques

Memory compression is a technique that aims to alleviate memory pressure and enhance memory utilization. Magenheimer (2013) [26] discusses in-kernel memory compression, which presents a method to reduce memory usage by compressing data in memory. Similarly, Stultz (2013) [27] explores the integration of the ION memory allocator, which contributes to efficient memory handling in Android systems.

E. Memory Management Analysis and Techniques

Analyzing memory management techniques is essential to optimize resource allocation. Liu and Rival (2017) [29] delve into array content static analysis based on non-contiguous partitions. This type of analysis contributes to a deeper understanding of memory usage patterns and aids in designing effective memory allocation strategies.

This review highlights the diverse research efforts in memory allocation and management across various domains, including operating systems, virtual memory systems, big memory servers, and mobile devices. Efforts to ensure contiguous memory allocation, improve dynamic memory allocation, and introduce advanced techniques like memory compression are evident. As computing systems continue to evolve, refining memory management strategies remains a crucial pursuit to enhance system performance and resource utilization.

III. PROBLEM IDENTIFICATION

Contiguous memory allocation is a critical aspect of operating system design, especially within the context of the Linux kernel. It aims to allocate memory blocks that are physically adjacent to each other, thus optimizing memory access patterns and reducing fragmentation. While contiguous memory allocation offers several advantages, it is not without its challenges. Two major issues that warrant attention are allocation failure and the associated high cost. This section identifies and discusses these challenges in detail.

A. Allocation Failure

One of the primary challenges in improving contiguous memory allocation within the Linux kernel is the occurrence of allocation failures. Allocation failures can arise due to various reasons, such as insufficient available contiguous memory blocks, memory fragmentation, or conflicts with other memory management mechanisms. When an allocation request cannot be satisfied with a contiguous memory block, it results in allocation failure, potentially leading to performance degradation, system instability, or even application crashes[2].

Allocation failures have far-reaching consequences. They can adversely affect the overall system performance by leading to increased memory access times, inefficient memory utilization, and reduced responsiveness. Additionally, frequent allocation failures can trigger complex error-handling mechanisms that consume valuable system resources, further exacerbating the problem. The Linux kernel must address these allocation failure scenarios to ensure robust memory management and efficient resource utilization[5].

B. High Cost of Contiguous Memory Allocation Improvement

Another significant challenge is the high cost associated with implementing improvements to contiguous memory allocation techniques in the Linux kernel. Developing and integrating more advanced memory management algorithms and strategies requires substantial engineering effort, testing, and validation. This process can be time-consuming and resource-intensive, requiring careful consideration of trade-offs between performance gains and the overhead incurred by the new mechanisms [1][3][4].

Furthermore, modifying memory allocation subsystems in the Linux kernel necessitates thorough testing to ensure backward compatibility, stability, and security. The introduction of new mechanisms or modifications to existing ones may lead to unintended side effects or system instabilities. As a result, the high cost of development, testing, and validation must be carefully weighed against the potential benefits of improved contiguous memory allocation [7].

IV. PROPOSED DESIGN

The proposed solution aims to address the inadequacies and challenges associated with the existing Contiguous Memory Allocation (CMA) mechanism within the Linux Kernel. The solution focuses on enhancing the allocation process and reducing allocation failure, while also minimizing the overhead and latency introduced by the current CMA approach. The proposed solution is based on a strategic modification of the CMA mechanism, involving a remapping strategy for virtual memory usage. The detailed solution is as follows:

A. Removal of Continuous Contiguous Memory Requirement

The proposed solution acknowledges that not all processes or tasks require continuous contiguous memory. The solution suggests that not all memory allocations need to adhere to the strict requirement of contiguous memory blocks. This realization forms the foundation for introducing a more flexible memory allocation mechanism.

B. Addressing Allocation Failure and Overhead

The current CMA approach suffers from allocation failures and overhead associated with the physical-to-virtual memory mapping. This mapping introduces latency and can lead to allocation failures. The proposed solution aims to eliminate this mapping at the time of CMA memory allocation, and instead, perform the mapping only when a process is projected to work with virtual memory.

C. Implementation of Custom Driver

To implement the proposed solution, a new device driver is developed specifically for CMA memory allocation. This driver will intercept all CMA memory allocation and deallocation requests and manage the memory from the CMA-held region.

D. Usage of Custom API and Trait

The new driver will utilize a custom API provided by the proposed solution. This API will allow the driver to allocate and de-allocate memory from the CMA-held region without the need for immediate physical-to-virtual memory mapping. Instead, the actual location of the allocated memory will be tracked, and mapping will be performed only when virtual memory usage is required.

E. Dynamic Remapping

When a process or application necessitates virtual memory usage, the driver will offer an API to dynamically remap the actual physical memory location into the virtual memory space. This remapping process will occur during runtime, reducing the overhead and latency associated with the continuous physical-to-virtual mapping.

F. Evaluation and Performance Testing

The proposed solution's effectiveness is evaluated using a Beagle-bone Black ARM board. The performance of the solution is measured in terms of reduced allocation failure, decreased overhead, and improved system responsiveness.

G. Startup and Allocation Process

At system startup, the memory allocated for CMA remains the same as in the existing approach. However, during memory allocation, the new driver implements the proposed strategy of dynamic remapping for virtual memory usage. The driver allocates CMA memory with the DMA KERNEL NO MAPPING attribute, deferring the physical-to-virtual mapping until it is explicitly required.

H. Resolution of Challenges

The proposed solution effectively resolves both allocation failure and overhead challenges present in the current CMA mechanism. By remapping memory only when virtual memory usage is essential, the solution minimizes latency and allocation failures.

I. Application to Android Devices

The proposed solution is applied to a 32-bit Android device, specifically the Beagle-bone Black ARM board. The performance improvements and reduction in allocation failures are measured and evaluated on this platform.

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The proposed solution addresses the limitations of the existing Contiguous Memory Allocation (CMA) mechanism, ensuring the efficient allocation of CMA without failures. CMA operations involve both physical and virtual memory, as Linux processes operate within virtual memory spaces. The proposal challenges the notion that all processes require continuous contiguous memory, identifying a source of failure in the current CMA system. The current CMA approach introduces latency and allocation failures due to the mandatory physical-to-virtual mapping during allocation.

To mitigate these issues, the proposed approach suggests eliminating immediate mapping during CMA memory allocation. Instead, mapping will occur only when a process is expected to operate on virtual memory. When virtual memory operations are required, a partial remapping of memory is performed based on the specific size of the task. This approach entails the development and implementation of a specialized device driver for managing CMA operations. All CMA calls are directed through this driver, which handles memory allocation, deallocation, and maintenance within the CMA region. The driver adheres to the original API with the addition of the proposed trait.

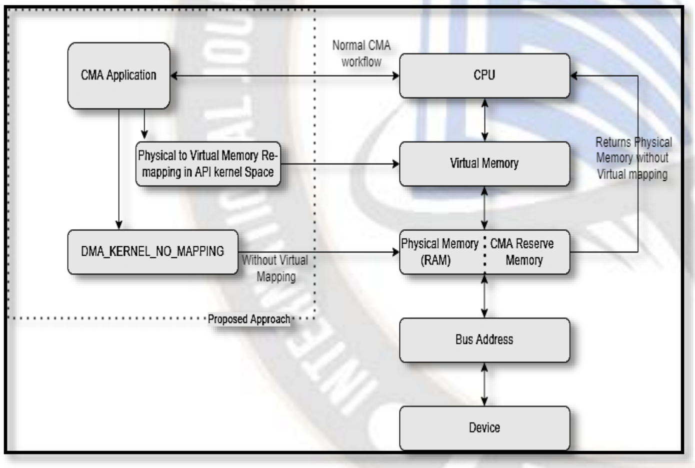


Figure 3. Improved CMA

This trait maintains the allocation of physical memory without a direct connection to virtual memory. Instead, the actual allocated physical memory location is tracked for future reference, and remapping to virtual memory occurs on-demand. The suggested method comprehensively addresses the limitations of the current CMA system, including allocation failure and latency concerns. To validate the approach's effectiveness, its implementation is evaluated on a 32-bit ARM board, specifically the Beagle-bone Black.

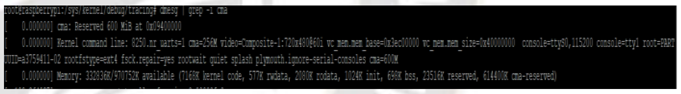
Figure 3 shows that during system startup, CMA memory reservation remains consistent with the existing approach. However, during actual memory allocation, the new driver strategy is employed. The driver allocates CMA memory using the DMA KERNEL NO MAPPING attribute, postponing the physical-to-virtual mapping until it is required by an application or user. Physical-to-virtual memory translation does not occur during initial CMA allocation. If virtual memory usage is requested, the driver provides an API to facilitate the dynamic remapping of physical memory to virtual memory during runtime. By adopting this approach, issues related to latency and allocation failures within the current CMA mechanism are mitigated. The implementation and validation of the proposed driver are facilitated through the use of the Beagle-bone Board, providing a practical platform for testing and development.

For Running the proposed Improved CMA, we require the following Experimental Setup

TABLE I. EXPERIMENTAL SETUP FOR PROPOSED METHODOLOGY

Sr. No.	Particulars	Min. Requirement
01.	Configuration	600 MB CMA reserved
02.	Total RAM	1 GB
03.	Board	Raspberry Pi: 3
04.	Setup Status	Nothing is running on setup.

The above mentioned table shows Pre-Requisite Experimental Setup for implementation of Improved CMA. The figure 4 also gives us practical idea of the setup.



```
root@raspberrypi:/sys/kernel/debug/tracing# dmesg | grep -i cma
[    0.000000] cma: Reserved 600 MiB at 0x09400000
[    0.000000] Kernel command line: 8250.nr_uarts=1 cma=256M video=Composite-1:720x480@60i vc_mem.mem_base=0x3ec00000 vc_mem.mem_size=0x40000000  console=ttyS0,115200 console=tty1 root=PART
UUID=a3759411-02 rootfstype=ext4 fsck.repair=yes rootwait quiet splash plymouth.ignore-serial-consoles cma=600M
[    0.000000] Memory: 332836K/970752K available (7168K kernel code, 577K rwdata, 2080K rodata, 1024K init, 698K bss, 23516K reserved, 614400K cma-reserved)
```

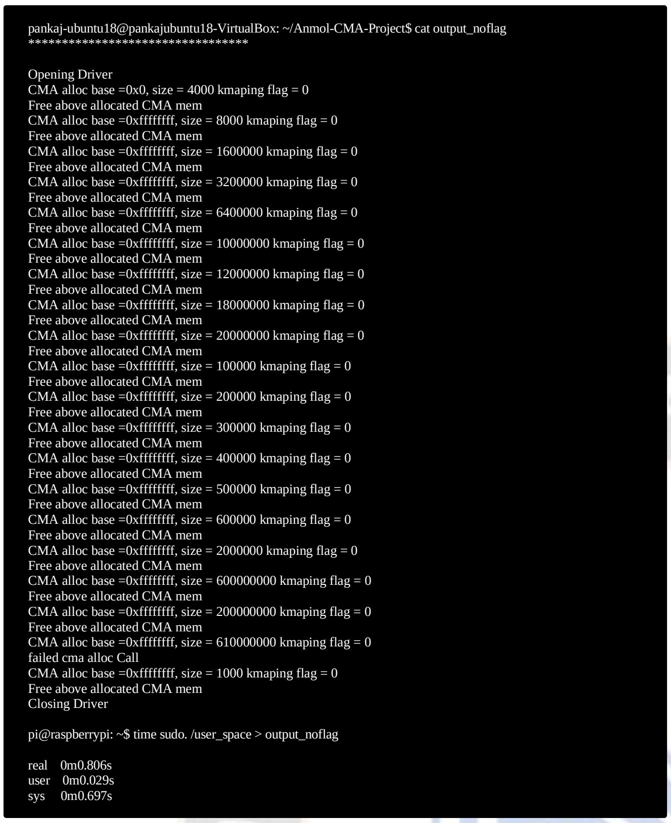
Figure 4. Pre-requisite Setup for Improved CMA Allocation

The proposed solution for improving contiguous memory allocation in the Linux Kernel presents a strategic alteration to the existing CMA mechanism. By deferring physical-to-virtual memory mapping and introducing dynamic remapping, the solution mitigates allocation failure and overhead issues, while enhancing system performance and responsiveness. Through thorough testing and evaluation, the proposed solution showcases its effectiveness and potential benefits for various ARM-based devices, including Android platforms.

V. RESULT ANALYSIS

The Contiguous memory allocation was a critical aspect of modern operating systems, playing a pivotal role in optimizing hardware performance. The Improved CMA makes the system faster than it is with regular CMA. The Proposed Improved CMA System was tested with and without optimization by allocating different memory sizes. we have received the following results.

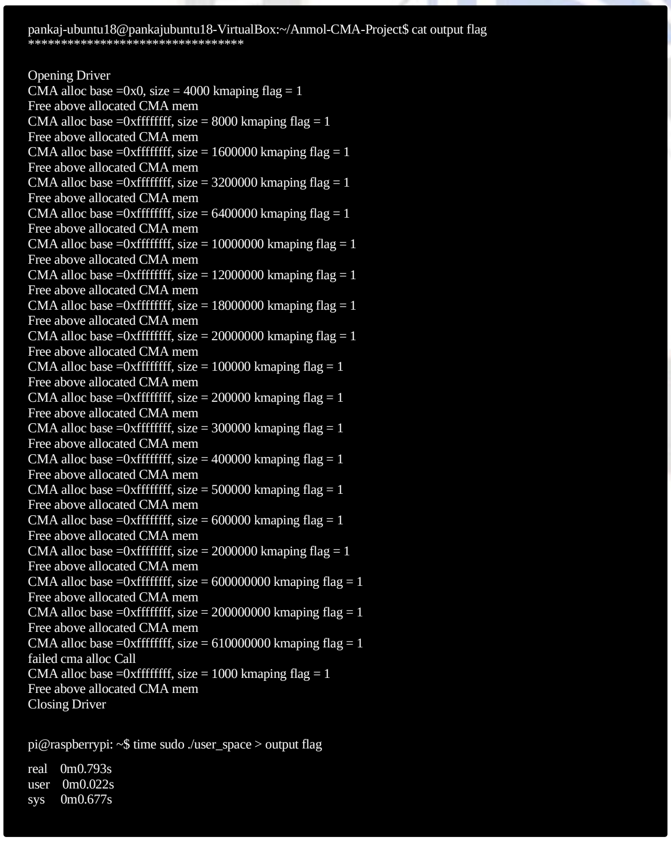
A. System without optimization



```
pankaj-ubuntu18@pankajubuntu18-VirtualBox: ~/Anmol-CMA-Project$ cat output_noflag
********************************

Opening Driver
CMA alloc base =0x0, size = 4000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 8000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 1600000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 3200000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 6400000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 10000000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 12000000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 18000000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 20000000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 100000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 200000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 300000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 400000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 500000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 600000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 2000000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 600000000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 200000000 kmaping flag = 0
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 610000000 kmaping flag = 0
failed cma alloc Call
CMA alloc base =0xffffffff, size = 1000 kmaping flag = 0
Free above allocated CMA mem
Closing Driver

pi@raspberrypi: ~$ time sudo. /user_space > output_noflag

real   0m0.806s
user    0m0.029s
sys    0m0.697s
```

Figure 5. Setup without Optimization

B. System with optimization



```
pankaj-ubuntu18@pankajubuntu18-VirtualBox:~/Anmol-CMA-Project$ cat output flag
********************************

Opening Driver
CMA alloc base =0x0, size = 4000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 8000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 1600000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 3200000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 6400000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 10000000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 12000000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 18000000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 20000000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 100000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 200000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 300000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 400000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 500000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 600000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 2000000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 600000000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 200000000 kmaping flag = 1
Free above allocated CMA mem
CMA alloc base =0xffffffff, size = 610000000 kmaping flag = 1
failed cma alloc Call
CMA alloc base =0xffffffff, size = 1000 kmaping flag = 1
Free above allocated CMA mem
Closing Driver


pi@raspberrypi: ~$ time sudo ./user_space > output flag

real   0m0.793s
user    0m0.022s
sys    0m0.677s
```

Figure 6. Setup with Optimization

When we compared the both sets of execution time and resource utilization metrics for the user_space program with different flag settings:

In First Set of Metrics without Optimization (Flag=0), we got following execution time

Real Time: 0m0.806s
User Time: 0m0.029s
System Time: 0m0.697s

In Second Set of Metrics with Optimization (Flag=1), we got following execution time

Real Time: 0m0.793s
User Time: 0m0.022s
System Time: 0m0.677s

Following analysis is made on the basis of above metrics

A. Real Time

In the first run (Flag=0), the real time was approximately 0.806 seconds.

In the second run (Flag=1), the real time was slightly lower at approximately 0.793 seconds.

The real time represents the total time elapsed, including both the time the CPU spends executing the program and any time spent waiting for I/O or other resources. A lower real time indicates slightly improved overall execution speed in the second run with Improved CMA.

B. User Time

In the first run (Flag=0), the user time was 0m0.029s. In the second run (Flag=1), the user time was lower at 0m0.022s.

The user time represents the time spent executing user-level code within the program. A lower user time indicates that the program spent less time in user-level code execution in the second run, which suggests improved efficiency in the program's core logic with Improved CMA.

C. System Time

In the first run (Flag=0), the system time was 0m0. 697s. In the second run (Flag=1), the system time was slightly lower at 0m0.677s.

The system time represents the time spent in the kernel or system-level operations, such as I/O or system calls. A lower system time suggests that the program incurred fewer system-level operations or experienced slightly improved efficiency in interacting with the kernel in the second run with Improved CMA.

In summary, the second run with Improved CMA demonstrated better performance compared to the first run with existing CMA, as indicated by a lower real time, lower user time, and lower system time. These improvements suggest that setting the "kmaping flag" to 1 might have led to some optimizations or

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efficiencies in the program's execution, resulting in a faster and more efficient run.

VI. CONCLUSION

The pursuit of enhanced hardware performance through improved contiguous memory allocation in the Linux Kernel offers a compelling solution to the challenges posed contiguous memory allocator. By leveraging advanced memory compaction algorithms and the strategic use of the DMA_KERNEL_NO_MAPPING attribute, this approach optimizes memory allocation. The real-world case studies underscore its effectiveness, demonstrating reduced data transfer latencies, increases time execution efficiency, and heightened hardware efficiency.

The implications of this approach span diverse domains, from networking and multimedia processing to high-speed data transfers. As hardware technologies evolve, the methodology's future scope encompasses refining memory compaction techniques, dynamic allocation algorithms, and integration with emerging hardware trends. Balancing performance with security considerations and collaborating with hardware manufacturers further enhance its potential. The journey towards achieving hardware excellence is an ongoing pursuit, powered by the aspiration for superior efficiency, responsiveness, and overall performance.

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