Freezing-based Memory and Process Co-design for User Experience on Resource-limited Mobile Devices

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Mobile devices with limited resources are prevalent, as they have a relatively low price. Providing a good user experience with limited resources has been a big challenge. This work finds that foreground applications are often unexpectedly interfered by background applications' memory activities. Improving user experience on resource-limited mobile devices calls for a strong collaboration between memory and process management. This article proposes *Ice*, a framework to optimize the user experience on resource-limited mobile devices. With Ice, processes that will cause frequent refaults in the background are identified and frozen accordingly. The frozen application will be thawed when memory condition allows. Based on the proposed Ice, this work shows that the refault can be further reduced by revisiting the LRU lists in the original kernel with app-freezing awareness (called *Ice*$^+$). Evaluation of resource-limited mobile devices demonstrates that the user experience is effectively improved with Ice. Specifically, Ice boosts the frame rate by 1.57x on average over the state of the art. The frame rate is further enhanced by 5.14% on average with Ice$^+$.

CCS Concepts: • **Software and its engineering → Main memory**; **Scheduling**; *Embedded software*; • **Computer systems organization → Processors and memory architectures**; *Embedded software;*

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1 Introduction

Mobile devices have evolved quickly in recent years. Among them, low-end and mid-range devices with relatively low prices and limited resources are prevalent in the market [3, 28]. As investigated, more than 1 billion of these low/mid-range smartphones are in use today around the world [66]. For these resource-limited devices, providing a good user experience has been a big challenge for smartphone vendors. However, people may experience screen jerking when some applications are cached in the **background (BG)**. This problem still haunts vendors, as it severely affects the user experience.

In mobile systems, when an app runs in the **foreground (FG)**, there are often applications alive in the BG. Most mobile phone users do not clean up these BG applications, which consume a significant amount of memory resources. When the memory is exhausted, mobile systems inherent in the design principle of Linux reclaim pages. Many prior studies are proposed to optimize the memory reclaiming algorithm [30, 43, 45, 47, 48, 62]. For example, in the Linux kernel, the LRU [23] algorithm is adopted, and page activity is defined based on the accessing history. SmartSwap [72] performs page reclaiming based on in-depth analysis of user behaviors. Acclaim [51] proposed a FG-aware page eviction scheme so that pages belonging to the FG application will not be reclaimed. With these solutions, inactive pages are efficiently identified and reclaimed. Fleet was proposed to improve the number of cached apps and hot-launch performance [35]. However, this article shows that the memory activities by BG processes often negatively impact the FG process, which has not been fully considered by existing solutions [30, 43, 45, 47, 48, 51, 62, 72]. As a result, frame dropping is observed when BG applications are on resource-limited mobile devices.

Our study on four typical scenarios (e.g., video call, short-form video, screen scrolling, and mobile game) indicates that the frame rate often drops below 30fps (frames per second) when multiple BG applications exist. Such frame rate is insufficient to provide a good user experience [56]. By collecting information from real-life smartphones, we provide four key observations. First, we observe that CPU contention is *not* the main reason. Second, while BG applications do not use much CPU, they often run tasks that need to access memory pages [33, 46]. As a result, many reclaimed pages are demanded soon in the BG, which causes frequent refaults. Third, memory reclaiming affects the FG application since priority inversion [32], and refault-induced memory thrashing amplifies such effects. Fourth, the problem in memory management is now actually caused by improper process scheduling. Based on these observations, we believe that a strong collaboration between memory management and process scheduling is a necessity, especially for resource-limited mobile systems.

Inspired by these observations, this article proposes Ice to collaborate memory and process management in resource-limited mobile systems for an optimized user experience. The key idea is to selectively inhibit the BG processes that are likely to cause page refaults. The process-inhibiting is driven by page refault. However, to realize the preceding design, there are several challenges. First, the cost of refault event tracking should be small. Second, the inhibiting target and intensity should be carefully controlled to ensure system stability and application robustness. Finally, Ice should be compatible with existing mechanisms in systems. To tackle these challenges, we propose two schemes: **refault-driven process freezing (RPF)** and **memory-aware dynamic thawing (MDT)**. Specifically, process inhibiting is triggered by the detected refault event. With the event-driven approach, the page refault can be aware quickly. The processes are inhibited by application-granularity freezing. In addition, Ice thaws the frozen applications periodically. The freezing and thawing cycles are dynamically tuned based on the memory pressure. We have implemented Ice on real mobile phones. Experimental results illustrate that Ice improves the frame rate by 1.57x on average over the state-of-the-art mechanisms [13, 23, 51, 65].

Based on Ice, this work revisits the memory reclaim process and shows that traditional memory reclaim mechanisms have the potential to be further improved. Specifically, many BG applications are killed when most of their pages have already been compressed or swapped. This is because, for an inactive application, its pages have a high possibility of being inactive. As a result, many reclaim operations become senseless and the resources are wasted. After freezing, these pages are allowed to be reclaimed. By coordinating application freezing with existing memory compression (e.g., ZRAM [24]) and the **low memory killer (LMK)** (e.g., [44]), which we call *Ice*$^+$ in this article, the user experience is further improved.

In summary, this work makes the following contributions:

— Based on the data collected from real-life users, this article reveals that the current user experience on mobile devices suffers from existing memory refaults with over-active BG processes.
— We propose Ice, which is a collaborative memory and process management framework for mobile devices. To the best of our knowledge, this is the first effort to solve the ineffective memory reclaiming problem with the help of process management.
— This article further proposes Ice$^+$, a novel solution to redesign the existing mechanisms (e.g., ZRAM, LMK) in mobile systems. Through LRU modification with app-freezing awareness, this work effectively addresses the resource waste issue mentioned previously.
— We have implemented Ice and Ice$^+$ on real-life mobile devices. Experimental results show that the user experience is significantly improved with Ice. Specifically, Ice improves the frame rate by 1.57x on average over the state-of-the-art mechanisms [13, 23, 51, 65]. The frame rate is further enhanced by 5.14% on average with Ice$^+$.

2 BG and Motivation

2.1 Memory Reclaim and Refault

Unlike server applications, mobile applications are often cached in the BG for fast switching and state restoration [31]. These cached applications consume limited memory resources, and the mobile system needs to perform page reclaiming when these applications fully consume the memory. In Android, when the free memory is lower than a threshold (low-watermark [41]), a lightweight kernel thread, *kswapd*, will be woken up to reclaim memory. Two types of pages are allowed to be reclaimed: anonymous pages and file-backed pages. Anonymous pages hold the run-time data generated and used by processes. File-backed pages are correlated to segments of files at the secondary storage. When performing reclamation, the anonymous pages will be stored in a compressed memory area (ZRAM [24]), the dirty (modified) file-backed pages will be written back, and the clean (unmodified) file-backed pages will be discarded directly.

Based on the page reclaim algorithm (e.g., LRU), inactive pages are selected as candidates for reclaiming. Reclaimed pages are transferred to *bio* instance, which represents an in-flight block I/O request in the kernel [8]. The instances are delivered to the block layer and further handled by the driver of the target block device. For anonymous pages, the ZRAM driver will be woken up to compress the content of the *bio* and store the compressed data on a virtual RAM disk. For file-backed pages, the UFS/eMMC driver will be woken up to send a dispatching command to the flash device and store the data in the secondary storage. When the reclaimed page is demanded

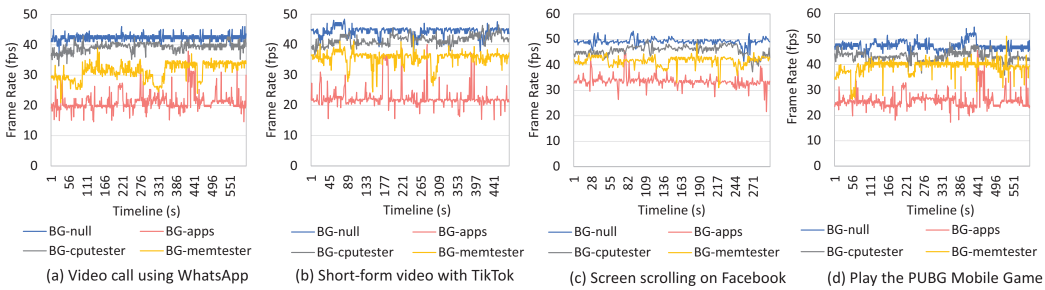


Fig. 1. Frame rate statistic of the four evaluated scenarios. The frame rendering performance is significantly lower when multiple applications are cached in the BG.

(so-called *page refault*[1]), these demanded pages is moved back to the main memory by triggering a page fault interrupt. Earlier reclaimed pages will be decompressed or read from the storage. The time between a page being evicted out and faulted in, which is called *refault distance* [21] in the Linux community, is hoped to be as long as possible.

2.2 Effect on User Experience

Page refaults can be classified into two types: FG refaults and BG refaults. The former occurs when earlier reclaimed pages are demanded by the FG application, whereas the latter occurs when demanded by BG processes. In this section, we will show that the user experience seriously deteriorates when refaults frequently occur in BG.

2.2.1 Workloads for Analysis. To understand the negative impact, we conducted experiments on a HUAWEI P20 smartphone with four typical real-life scenarios. The phone is equipped with HiSilicon Kirin970 core, 6GB DDR4 RAM, and 64GB UFS2.1 Flash.
Scenario A: Video Call. In this scenario, we use WhatsApp and initiate a video call with a remote user. The picture on the screen changes with the expression and action of the remote user.
Scenario B: Short-Form Video Switching. Today, people are spending more and more time on short-form videos when using smartphones [12]. We evaluated this scenario with TikTok. Specifically, we play the videos recommended by the application, then switch to the next. We repeat the playing and switching operations.
Scenario C: Screen Scrolling. Screen scrolling is one of the most common actions in smartphone usage. We browse the *timeline* of Facebook to explore the user experience of screen scrolling.
Scenario D: Mobile Game. Users have a high demand for the fluency of mobile games. We use PUBG Mobile, a popular real-time battle royale game on smartphones, to evaluate the user experience in this scenario.

2.2.2 Effect on Frame Rate. The deterioration of user experience from a jerky screen, referred to as "jank,"often occurs when BG applications exhaust the memory. To quantify the user experience, we analyze the frame rate in the evaluation. It depicts whether a user can smoothly interact with the screen. Generally, more frames rendered per second provide a better user experience. FPS (frames-per-second) has been widely adopted as the metric of frame rate.

For each scenario, we configure BG applications with two cases: *BG-null* and *BG-apps*. "BG-null" refers to the case where the target applications (e.g., WhatsApp, TikTok, Facebook, and PUGB Mobile) run without applications cached in the BG. "BG-apps" refers to the case where eight applications are cached in the BG before running the target applications. We select a period from

[1]Page refault is defined as the case where the page fault happens on the previously reclaimed page [52].

Table 1. CPU Utilization with $N(0 \sim 8)$ Applications in the BG

Number of BG Applications	CPU Utilization	
(No FG App)	Average Value	Peak Value
0	43%	52%
2	46%	58%
4	47%	63%
6	51%	67%
8	55%	69%

each of the four scenarios as a sample, and the FPS of the FG application is presented in Figure 1. The X axis represents the timeline, and the Y axis represents the FPS. This shows that FPS is significantly degraded with applications in the BG. For example, when having a video call without caching applications (blue line in Figure 1(a)), the frame rate is 42.2fps on average. However, with eight applications cached in the BG, the video call becomes jerky. The cached applications are Twitter, Amazon, Angry Birds, YouTube, Skype, Chrome, Uber, and Google Maps. In this case, the FPS (red line in Figure 1(a)) is reduced by 51.7% on average. Even though differences depend on the application characteristics, noticeable FPS degradation is observed in all scenarios.

2.2.3 Root Cause Analysis. The FPS of the FG application could be affected by BG applications' CPU contention or memory contention. In this subsection, we examine both possibilities.

CPU Contention. BG applications introduce additional CPU consumption. To explore how much CPU resources are consumed by BG applications, we conducted the following evaluation. We monitor the CPU utilization with no application in the BG and FG. The CPU utilization is 43%, on average. The Linux kernel and Android framework's tasks take up the CPU resources. Then, we cache N applications in the BG. The BG applications stay in the BG for 10 seconds with no FG application. To avoid bias, BG applications are selected randomly from 20 popular applications (detailed in Section 5.1). Each evaluation is conducted for 10 rounds, and the average is shown in Table 1. The average CPU utilization is increased to 55% when N equals 8, and the peak value is 69%. CPU information is collected by Perfetto [67]. The preceding evaluation indicates that BG applications are not CPU-intensive in general.

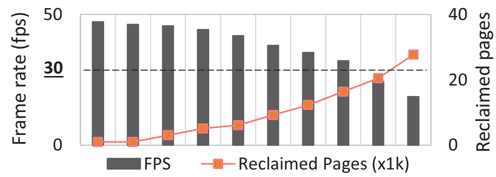
To understand whether the FPS is affected by CPU, we configure the BG applications with an additional case: *BG-cputester.* In this case, BG applications are replaced by cputester, a self-developed tool that occupies CPU resources but does not introduce big memory pressure. The cputester occupies 20% CPU utilization in the BG, similar to the measured CPU consumption of BG applications. Also as shown in Figure 1, when compared to the BG-null case, the FPS is only reduced by 6.3% on average with cputester in the BG. This indicates that the steep FPS reduction in the BG-apps case is not caused by CPU consumption of BG applications.[2]

Memory Contention. In the BG-apps case, the memory is almost exhausted (more than 90% of the memory space is unavailable) by BG applications, so memory reclaiming occurs when running the target application in the FG. The FG application may wait for the completion of the reclaiming process which is *non-preemptive* [32], even though the former has a higher priority, thus causing priority inversion. Frequent refault increases the possibility of such priority inversion because more page reclaiming is required to save memory space. To analyze the memory factor separately, we replace the BG applications with memtester [64], an open source tool that occupies memory but does not induce big CPU consumption. The size of occupied memory is 5.52GB in total, similar to that of the BG-apps case.

[2]Note that Android is now differentiating the FG application from BG applications. For example, the FG application is always allowed to use CPU cores exclusively, whereas BG applications must share the cores [15].

Case	Reclaim	Refault
BG-null	76	3
BG-memtester	55,637	1,351
BG-apps	102,581	38,924

(a) The number of reclaimed and refaulted pages in total



(b) Correlation between frame rate and memory operations

Fig. 2. Frame rate analysis. Frame rate degraded when suffering frequent refaults.

Figure 1 shows that the FPS is reduced by 27.8% on average in the BG-memtester case when compared to the BG-null case. We traced the process of frame rendering (e.g., `animation`, `measure`, `layout`, and `draw`) using Systrace [20]. When the available memory is smaller than the watermark threshold, a high number of frame rendering tasks are blocked by memory reclaiming tasks. As a result, the FG application with a high priority is blocked by the BG processes with a lower priority. Such priority inversion is one of the main reasons for FPS degradation [32]. This demonstrates that memory contention can significantly affect the FG application.

BG Refault. When the memory is filled by memtester (yellow line in the figure) instead of mobile applications (red line in the figure), the FPS degradation compared to that of BG-null is much smaller. Take Figure 1(a) as an example. We can see that the FPS in the BG-memtester case stays at a low level (around 25fps) for a much shorter time. The frame rendering tasks still have an opportunity to run efficiently when enough memory space has been reclaimed. On the contrary, in the BG-apps case, the FG application constantly suffers interference.

One big difference between normal applications and the memtester is that a large number of reclaimed pages are demanded again in the former case. By checking the processes causing page refaults, it can be found that most of the refaults occur in the BG. The refaults result in many invalid memory reclaiming operations. Hence, more memory reclaiming operations are detected in the BG-apps case. Specifically, when compared to the BG-memtester case, 84.4% more memory reclaiming operations are detected in the BG-apps case (Figure 2(a)). BG applications are rarely CPU-intensive tasks, but their execution always needs to access memory pages [33, 46]. As a result, BG applications *indirectly* but *constantly* interfere with the FG application by inducing memory-related activities.

Note that the frame rate is affected by many factors during the evaluation, like user operations when interacting with the FG app and the resources state and resource status at different times. This is the reason for the significant fluctuations in frame rate. For example, we can see an initial decrease in frame rate and then an identical frame rate as the FG app in Figure 1(a). During video calls, differences in visual content and unstable network signals can lead to unstable frame rates. Fortunately, although frame rate fluctuations are affected by various factors, by averaging, we can clearly see the differences between different cases. Moreover, from the comparison between BG-null and BG-memtester, we can see the persistent loss of frame rate. This is because even though no refault-induced memory threshold, memory demand still occurs during the app usage. As a result, memory reclaim operations always occur in the BG, consuming CPU resources and sometimes blocking the main thread of the FG application (can be observed through Systrace).

To understand such effects, the BG-apps case is further analyzed. Specifically, we split the collected information from the four-scenario evaluations into time slices. Each time slice contains 30 seconds of frame rendering information. Then, these time slices are sorted according to the BG refault numbers. Based on that, the frame rates are compared from the [0th, 10th]-percentile to the [90th, 100th]-percentile. Figure 2(b) illustrates that the frame rate seriously deteriorated in the time window that BG refaults frequently occur. Specifically, the frame rate of the target applications is

47.2fps on average when refault rarely occurs ([0th, 10th]-percentile). It is reduced by 60.6% when suffering frequent BG refaults ([90th, 100th]-percentile). In addition, more pages are reclaimed in a fix-sized time window when more BG refaults occur. This illustrates that frequent BG refaults can induce more memory reclaims, thus interfering with the FPS of the FG application indirectly. Usually, frame dropping will typically occur with FPS lower than 30 [56]. So mobile users often suffer not-smooth interaction on low/mid-range devices, when suffering such steep FPS reduction.

BG refaults amplify the interference to the FG application through three sources. First, more memory reclaiming operations are required to release enough space. These system activities could block the frame rendering task required by the FG application. Second, BG refault increases the I/O pressure. On one hand, file-backed pages may need to be read from the flash storage when suffering refault. On the other hand, the system could write back more file-backed pages to make room for the refaulted pages. Third, even though BG applications do not consume a lot of CPU resources, their activities in the BG still create memory interference to the FG applications.

Figure 2 shows fewer refaulted pages from the BG apps (39k) than reclaimed pages from the testing app (56k). However, there is an even less performance penalty at the beginning of the testing-app experiment than in the BG-app experiment in steady state. This is due to two reasons. First, by monitoring the value of *pswpout* through *#cat /proc/vmstat* in Linux, we observe that the page reclaim process occurs throughout the entire process of FG application usage rather than reclaiming all 56k pages in the initial stage. As explained previously, the frame rate degradation during certain periods is due to interference from other factors (e.g., signal). It does not mean that memory reclaim is concentrated during this period. Second, generally, a refault's effect on application threads is more significant than reclaim. In the Linux kernel, memory reclaim is conducted in an asynchronous approach (by waking up *kswpd* daemon), except when the Linux kernel enters the *direct_reclaim* code path. Differently, refault is always performed synchronously. When suffering refault, the corresponding thread must wait until after refaulted pages are allocated memory space by the buddy system. What is worse, since the memory is exhausted, the page allocation cannot be completed before enough memory is released. As a result, when suffering frequent refault, the suspension time of threads has significantly increased. It is right because of the combination of the preceding two reasons that when the FG app runs in the BG-app case, the resource situation is in a more severe state when compared to the BG-memtester case.

3 BG Refault Analysis

In this section, we extend our analysis to illustrate how BG refault is a widespread problem in mobile systems. Then, we analyze the cause and show the opportunity to redesign the memory and process management in mobile systems.

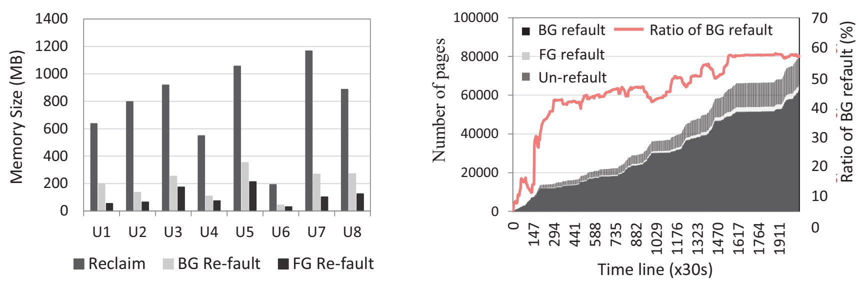
3.1 BG Refault Study from User Data

To understand page refaults in real usage scenarios, we provide eight Android smartphones to volunteers[3] for daily usage. The details of the smartphones are shown in Table 2. We instrument the Android source codes on the smartphones to collect the required system information (with the user's authorization). Our instrumentation includes information on the number of refault pages, the number of reclaimed pages, the process each refaulted page belongs to, the process information of the FG application, and the timestamp of each page reclaiming/refaulting operation. Volunteers install and use applications following their habits. The information in the smartphones is collected over 1 month.

[3]The volunteers are 18 to 60 years old.

Table 2. Details of the Tested Smartphones

Device Version	CPU	Memory Size	Operation System	Volunteer ID
P20	Kirin 970	6GB	Android 9	User-1, User-2
P40	Kirin 990	8GB	Android 10	User-3, User-4
Pixel3	QSD 845	4GB	Android 10	User-5, User-6
Pixel4	QSD 855	6GB	Android 10	User-7, User-8



(a) Refault ratio analysis (b) Refault ratio on P20 over time

Fig. 3. Page refault study. The refault ratio is high, and most of the refaults are caused by BG processes.

Figure 3(a) shows the number of reclaimed and refaulted pages per day for all eight smartphone users. It indicates that 39% of evicted pages are moved back, on average. In the figure, the refault ratio refers to all refault events divided by all reclaim events up to that point in time. In addition, more than 60% of refaults are caused by BG processes instead of FG processes. The memory state over time in each device is also monitored. The cumulative numbers of evicted and refaulted pages are recorded. The information is collected every 30 seconds. Take HUAWEI P20 as an example. Figure 3(b) shows several observations. First, the number of refaulted pages increased when more pages were reclaimed. Second, the refault ratio was low at the beginning but finally fluctuated at a high level (38%). Third, the main contribution of the high refault ratio is BG refault. As presented in the figure, 65% of refaults are caused by BG processes. The system wastes more available resources than necessary since many reclaiming operations are invalid. This phenomenon happens on all evaluated smartphones.

3.2 Sources of BG Refault

A well-known source of BG refault is runtime **garbage collection (GC)** [31, 46], which is responsible for collecting the unused memory space in a managed language, such as Java. Android applications run on the Android runtime (Dalvik before Android 4.4 and ART on later versions), which enables the GC feature. It may be triggered not only when allocating new objects on the heap but also when the application is in the BG. When GC runs, reclaimed pages may be moved back. Some studies have been proposed to co-design GC with memory swapping (e.g., [35, 46]). However, in this section, we show that GC is not the only source of BG refault. In daily usage, users are accustomed to directly switching applications to the BG instead of manually killing them. Therefore, all applications shown in Figure 4 have the possibility of being in the BG. In addition, for quick switching and history restoring, mobile OSes encourage caching them in the BG.

To explore the sources, we conduct a study with 40 popular applications. The basic method is to reclaim all pages of the application manually. Then we trace which pages are refaulted back and which processes cause the refaults. Specifically, we launch and run the tested application, then switch it to the BG. After that, we reclaim all file-backed and anonymous pages of the application

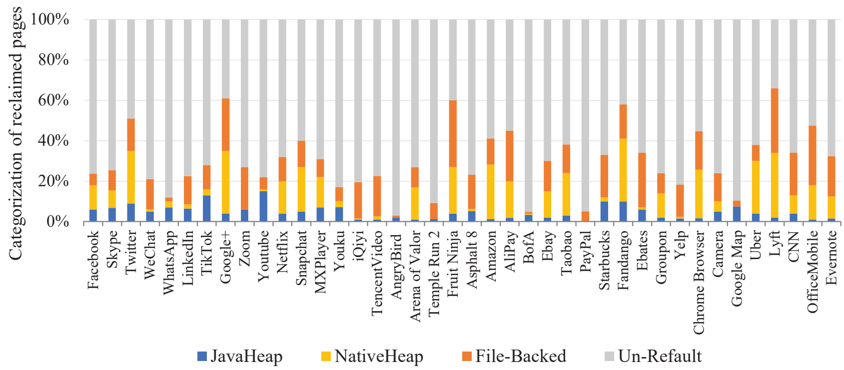


Fig. 4. Categorization of reclaimed pages. Among the reclaimed pages of each application, both anonymous and file-backed pages suffer BG refault.

by enabling the per-process reclaim feature in the Linux kernel [22]. The numbers and types of refaulted pages within 30 seconds are detected with the command `$cat /proc/{pid}/status`.

Figure 4 shows the categorization of refaulted pages. More than 30% of reclaimed pages are moved back in total. Among them, 48.6% are file-backed pages and 51.4% are anonymous pages. Furthermore, more than 56.6% of the refaulted anonymous pages are maintained in the native heap, and 43.4% are maintained in the Java heap. The native heap is allocated by using the underlying `malloc` and `free` mechanisms of the OS. The Java heap contains the instances of Java objects. Since the tested application has not switched to the FG, all detected refaults occur in the BG. The proportion may be different when the application version or smartphone platform changes. But the phenomenon of frequent BG refault was widely observed.

Page refaults in the Java heap are mainly caused by the GC thread [59]. However, there are still 77% refaults observed, even when we disabled the "idle runtime GC" feature. We traced the tasks run on each core and found that *the BG applications are not as quiet as expected*. On each tested platform, we first obtain the process that runs on cores when no applications run in either BG or FG. In this case, more than 90% of the CPU usage time comes from system service tasks (e.g., *Binder*, *HeapTaskDaemon*, and *kworker*). Then we trace the processes that occupied CPU time after caching eight applications in the BG. No application runs in the FG. We conduct such an evaluation for 10 rounds. The BG applications (detailed in Table 3) are selected randomly in each round. As evaluated, more than half (58%) of BG applications are observed to run on CPUs, including the main thread of Facebook, Twitter, WeChat, and TikTok. Further, more Android services are executed—for example, the location tracking (*gms.location.LocationListener*) thread. In addition, any application that has been granted location/microphone access could be running in the BG and making records [1, 2, 9]. In addition, investigation illustrates that many applications were not developed in a system-friendly approach [33]. They may consume constrained resources in a wasteful manner. Some of them run in the BG to ensure its optimal performance, and some even have bugs in their design. For example, Facebook had a buggy release [36] that left the application doing nothing but stay awake and running in the BG.

Although Android/Linux OSes prefer to reclaim pages that belong to processes that are "inactive"or in the BG [23], a large number of refaults are still observed in modern systems. This is because the BG processes can still be executed even if set with low priority in practice. What is worse, the OS is not aware of their impact on reclaimed pages. These limitations motivated the design of Ice.

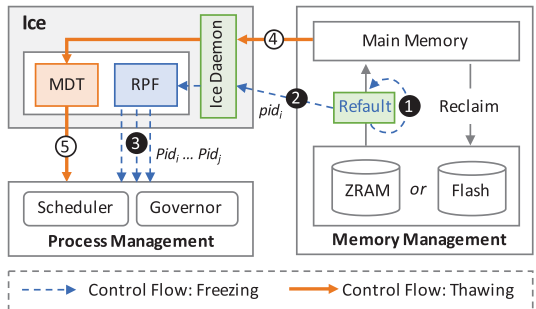


Fig. 5. Ice overview. Ice detects the refault event and transfers the ID of the process causing refault to the RPF component for freezing (see the dashed lines). The MDT component monitors the memory pressure and thaws the frozen processes periodically (see the thick lines).

4 Design

4.1 Overview

Ice is beneficial for reducing refault. As shown in Figure 5, Ice bridges the memory management and process management subsystem. The basic idea of Ice is to freeze the active process that will cause page refault and thaw them periodically. Two components are proposed to realize the features: RPF (detailed in Section 4.2) and MDT (detailed in Section 4.2.3). In addition, an Ice daemon is maintained to communicate with existing system modules.

The control flow of process freezing and thawing are shown in ❶ through ❸ and ④ and ⑤, respectively: (1) Ice detects the refault event in kernel space.; (2) The process ID (pid_i) that induces page refault is obtained and delivered to the RPF component; (3) Ice finally determines the freezing targets ($pid_i, \ldots, pid_j$), then sends commands to the process management subsystem to inhibit the activity of selected processes; in addition, the MDT component monitors memory pressure (4) and intermittently thaws the processes (5). The thawing cycle is dynamically tuned based on the memory pressure.

With RPF and MDT components, the following challenges are tackled in the design. First, the refault event can be monitored with low overhead and respond quickly. Second, the freezing target and intensity are intelligently controlled. Finally, the proposed solution is compatible with existing mechanisms in the system. Ice has been deployed on multiple Android smartphones without invasive modification in mobile applications or hardware infrastructure.

4.2 Refault-Driven Process Freezing

RPF aims to freeze the active BG processes in case of sustained refault in the BG. Process freezing [42] is a mechanism by which processes are forced to hibernate. Once a process is frozen, it will never be executed before thawing and thus will not induce refault. In our design, RPF selectively freezes the BG processes that cause page refault instead of aggressively freezing all BG applications. This is because it always takes a longer time to switch a frozen application to the FG. To minimize the overhead, RPF only freezes the BG applications that may cause memory thrashing. Our experiment on real platforms in Section 6 will show that selective freezing is enough to inhibit the reclaim/refault behaviors in the BG.

Therefore, identifying the BG process that will cause frequent refault is a critical issue. One approach is to predict based on historical information through machine learning, like the Markov model [68, 70]. However, the overhead to maintain the machine learning model is high. A lightweight refault identification method is required. This article finds that a process often demands

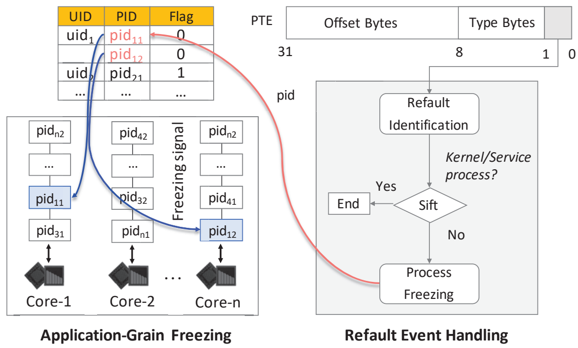


Fig. 6. RPF overview. It consists of two core components: refault event handling and application-grain freezing.

multiple pages at a time. The source of multiple adjacent refaults is often the same application. Ice freezes the BG process once the first refault is identified. An event-driven freezing scheme is proposed.

4.2.1 Refault Event Handling. RPF follows the ECA (event-condition-active) rule [10], which can be described as follows: fired *events* that satisfy the *conditions* will trigger *actions* to execute. Specifically, RPF detects the refault event in the kernel space. It then determines whether the process causing the refault is a BG process and if it is allowed to be frozen. Processes that are not allowed to be frozen, like kernel or service processes, are sifted. Then, the ID of each "freezable"process is delivered to an application-grain freezing module for further processing.

Refault Identification. As illustrated in the right part of Figure 6, the refault event is detected based on the **page table entry (PTE)**. If a page has been evicted to the storage, one flag bit in the PTE will be modified. Specifically, bit-0 of the PTE is reserved for the `_PAGE_PRESENT` flag. When a page fault occurs, the system will access the PTE to obtain the page address. By checking this flag bit when suffering page fault, RPF can identify whether the required page was previously evicted or not. In this way, the refault event can be detected. The modern Linux kernel has already provided an interface to obtain the refault-related information (`shadow entry` [26]). For simplicity, we apply this interface to identify whether refault events occur.

Process Selection. When a page refault event is detected, RPF identifies which process the page belongs to. Then it judges whether the process is freezable. Note that some processes are not allowed to be frozen. RPF first checks the process type. Kernel processes (e.g., `kswapd`, `kworker`) and Android services (e.g., UI thread, GC thread) are identified and will not be frozen. Here, a technical challenge is to accurately identify which process caused the refault. In the Linux kernel, page refaults start from the page fault interruption. It is easy to obtain the page table and the virtual address of this fault (by page fault handler) in the Linux kernel, and we can determine which process caused this page refault. In this way, the relationship between the memory page and the process is identified.

Response to the Refault Event. After process sifting, the process that causes refault will be handled. RPF tries to inhibit the process activity by freezing. Refault events can be detected in nearly real time, and RPF can respond immediately as they occur. We realized that simply freezing a single process may affect the corresponding mobile application as a whole. Therefore, in this work, freezing is conducted in the application granularity.

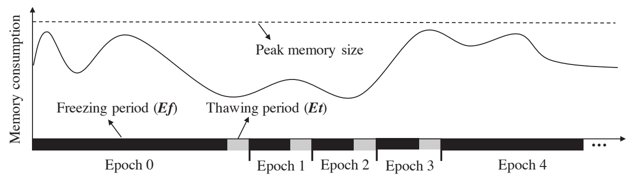


Fig. 7. Memory-aware heartbeat.

4.2.2 Application-Grain Freezing. RPF conducts freezing in application granularity. It maintains a mapping table between the application and process. The former is represented by the **unique ID (UID)**. Once installed, the UID is fixed. Applications in the user space have no permission to access these UID bits, as this is handled by the OS or hardware. As investigated, each application generates several processes when running. The mapping table is updated when an application is installed, deleted, or launched. Based on the mapping table, RPF can obtain the process information during the lifecycle of mobile applications. When RPF tries to freeze a process, it checks the mapping table, identifies which application the process belongs to, and then sends freezing signals to the target processes. The processes react to the signals by calling function `try_to_freeze()` [25], which makes them hibernate until receiving the signal for thawing. In this way, the BG applications that cause page refault can be frozen.

In the design, the mapping table is maintained in the kernel space so that RPF can index the table quickly. There is no communication between the kernel and user space during the freezing process. The only cross-space communication happens when updating the mapping table. Specifically, we collect the application information from the Android framework and deliver it to the kernel through the proc file system. A function is predefined in this file system through `file_operations()`. When writing protocol string to the `/proc/{pid}/ice-mp` node, this function will be called. This function receives the application information (e.g., UID, PID, state) and updates the mapping table. In the lifecycle of a mobile application, the preceding information is seldom changed, when compared to the frequent process indexing operations of RPF, so such cross-space communication is acceptable.

RPF freezes processes in application granularity. This is because one application always maintains several processes at the same time. We observed that these processes belonging to the same application always depend on or communicate with each other. By freezing the processes together, application robustness is enhanced. In this work, we freeze applications rather than kill them straightforwardly because the frozen application can still be fast switched (hot launched[4]) and the history-state can restore.

4.2.3 Memory-Aware Dynamic Thawing. This article proposes MDT, a mechanism to give frozen applications a chance to run. How long the applications should be frozen in the BG should be carefully calculated so that its impact on memory is minimized. The freezing intensity is tuned dynamically. Theoretically, the intensity should increase if the memory pressure is high and reduce when the pressure is alleviated. Here, freezing intensity is quantified with the ratio of *freezing duration* and *thawing duration*. The higher the freezing intensity is, the higher the probability that applications are frozen in the BG. Motivated by this, this article proposes MDT.

As illustrated in Figure 7, MDT maintains a heartbeat in the system. Each heartbeat epoch is divided into two periods: the freezing period and the thawing period. At the beginning of each

[4]In general, several applications can reside in memory after execution. These applications are hot launched without needing to build a new process or generate application activities [47].

epoch, the selected applications are frozen for E_f seconds and then thaw for E_t seconds. The epoch length is tuned based on the memory state. When memory pressure increases, the freezing period should be lengthened; otherwise, the freezing period is shortened. In $epoch_i$, the target processes are frozen for $E_f(i)$ seconds and thawed for $E_t(i)$ seconds. After that, MDT detects the size of current available memory and update $E_f(i)$, then enters the next epoch $E_f(i+1)$. MDT sends signals to the target processes at the beginning of each freezing and thawing period. MDT maintains only one heartbeat mechanism no matter how many applications are installed.

Suppose an application triggers a page refault and needs to be frozen at time T. If T occurs in the freezing period, where $0 < T \leq E_f$ in an epoch, this application will be frozen instantly and thawed at time E_f, then allowed to run in the following E_f seconds until the next epoch comes. If T occurs in the thawing period, this application will also be frozen instantly but will not be thawed until the thawing period of the next epoch. MDT dynamically tunes the freezing intensity by changing the ratio of E_f to E_t. This ratio (R) is tuned based on the memory watermark [41]. Specifically,

$$R = \frac{E_f}{E_t} = \delta \times 2^{\lceil \frac{H_{wm}}{S_{am}} \rceil}. \tag{1}$$

Here, H_{wm} stands for the high watermark, and S_{am} stands for the size of available memory. δ is a weight coefficient. In a given system, the high watermark H_{wm} is determined at the system initialization phase. So R increases when the size of available memory S_{am} is small. As a result, the freezing intensity is enhanced with the increase of memory pressure. To easily control the freezing intensity, E_t is set as a unit time, 1 second, by default. So the length of an epoch can be tuned by simply changing the value of E_f.

Before adopting the freezing/thawing approach, this article explored various schemes, such as priority reduction. However, our evaluation shows that even the process with the lowest priority can still run frequently. The reduction of page refaults is not significant. What is worse, the opportunity to suffer page refaults is unpredictable. By performing application freezing and thawing, the refaults in the BG can be strictly constrained and managed.

4.3 Ice$^+$: Co-Design Ice with Existing Mechanisms

With Ice, BG application-induced refaults are reduced. This work further co-designs Ice with existing memory and process management subsystems for user experience optimization, and proposes Ice$^+$. Ice$^+$ aims to alleviate the following problems:

- In the original system, memory pages are reclaimed (e.g., compress or swap) when the watermark exceeds a threshold. If reclamation cannot solve this problem, LMK will be triggered for more aggressive memory releasing. Both memory reclaim and aggressive memory releasing follow the LRU rule. The OS tends to select inactive pages or applications as the victim. Unfortunately, the reclaimed pages always belong to the inactive application. As a result, many pages are swapped to the compression region or swap partition and then released because of LMK. The "reclaim-then-killing"phenomenon leads to two problems. First, the resources are wasted. Second, most pages of the selected application have already been reclaimed, and app killing cannot release enough space as expected. As a result, we observe that multiple applications are often killed consecutively.
- The original system uses LRU lists to help reclaim pages. This is because the least recently used pages have a lower possibility in the future. When enabling the freezing feature of Ice, many pages will not be accessed even though they have high activity (caused by BG activities) in the history. The traditional LRU algorithm does not consider this problem. Ice$^+$ aims to modify the LRU so that memory pages can be evicted with minimized refaults.

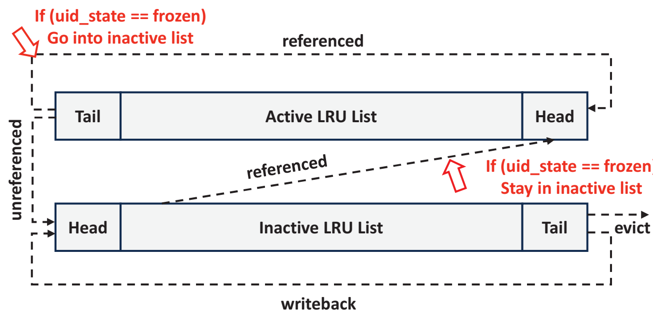


Fig. 8. Freeze-aware page evict scheme of LRU lists.

We co-design Ice with the memory reclaim and process killing schemes in the original system. The basic idea is to reclaim or kill an application but will not do the two operations on one. It is practicable as Ice performs freezing in app-grain.

4.3.1 Freezing-Aware Eviction. Based on the coordination of Ice and the original memory reclaim, this article proposes a freezing-aware eviction strategy. Ice$^+$ evicts the pages of one frozen app together instead of following the LRU scheme straightforwardly. This approach has two advantages. First, frozen pages can be identified as inactive immediately, free from the misleading of accessing history in LRU. Second, Ice freezes in application granularity. By performing specific operations (reclaim or kill) on a frozen application, resource waste caused by reclaim-then-kill can be avoided.

To realize freezing-aware eviction, we must know whether a page belongs to frozen applications. This list of frozen applications can be obtained based on the mapping table in Section 4.2.2. Ice$^+$ notifies the UID of the application to the kernel when it is frozen or thawed. As shown in Figure 8, page migration on LRU lists is driven by memory pressure. Rarely used pages in the active list go to the inactive list. Pages are taken from the tail of the inactive list to be freed. Pages having the reference bit set will be moved to the head of the active list and the reference bit is cleared. If a page is dirty, its content will be written back and the page will be moved to the head of the inactive list. Ice$^+$ lowers the priorities of frozen pages and moves them out of LRU lists quickly. Thus, Ice$^+$ can extract space from frozen applications for the FG application efficiently.

4.3.2 Process Killing with Ice. Pages belonging to the same application will be processed in the same approach (compression or kill). When evicting the page append on the tail of the inactive LRU list, Ice$^+$ first checks its UID. Based on the mapping table, Ice$^+$ knows whether the corresponding application is frozen. The size of the mapping table is small, and all of its content is stored in the memory. Thus, the state can be obtained immediately. For example, suppose page i of app w is compressed using ZRAM, and the other pages belonging to w are allowed to be compressed too. But the state of w in the mapping table will be flagged as “unkillable.”In other words, when the LMK engine selects target applications, w will be skipped. In this way, the resource wastes are saved.

4.4 Implementation and Discussions

4.4.1 Whitelist for Safety. To ensure that the freezing operation is user imperceptible, Ice exploits a whitelist approach. The basic idea is to add perceptible applications to the whitelist. These applications are not allowed to be frozen. In practice, Android now has a mechanism to identify which applications are user perceptible [14]. First, the application that is calling interaction activity (called the `onResume()` interface) is identified as an FG application by the Android framework. This application is critical and should not be frozen. In addition, some applications in the BG are user perceptible. For example, the application which is playing music or downloading files in the BG should not be frozen. Android identifies these applications by checking whether they are calling the `startService()` interface. Android provides a priority score mechanism for these applications. Ice can obtain the score (*adj* value in Android [14]) of each process by `#echo /proc/pid/oom_score_adj`. In the system, the score of FG processes is set to 0, and perceptible BG applications are set to 200 by default. Normal BG processes have a higher score. The applications with low process scores (≤200) are added to the whitelist.

We realize the whitelist by delivering the scores to the kernel space and recording them in the mapping table. The whitelist is updated when the scores are changed. For example, the downloading task in the BG is finished or the FG application is switched. In addition, the whitelist can be managed offline. If vendors wish to optimize some specific applications in the BG, such as an antivirus malware tracker or the applications that need to receive calls or messages, they can put the UID of these applications into the whitelist in advance. When Ice determines the freezing target, it checks the whitelist to ensure that critical or perceptible applications will not be frozen.

4.4.2 Thawing on Launch. The frozen applications will not respond to the user input even when it switches to the FG. To address this problem, Ice detects application switching behavior. When a frozen application is switched to the FG, Ice will thaw it before displaying the application on the screen. The thawing operation is asynchronous and will not be interrupted by the MDT scheme.

The preceding optimizations ensure that Ice's operation is user imperceptible. The source code of the Linux kernel is modified to enable Ice. Ice introduces new features in the system with no invasive modification in mobile applications. To enable Ice, people need to recompile the Android project and replace the `system.img` and `boot.img` in *fastboot* mode. Ice can be implemented on other Android devices with diverse versions and ease of maintenance.

4.4.3 The Implementation of Ice in the Future. Ice could be more useful for future generations of mobile devices. First, with new flash (e.g., QLC) chips, storage lifetime is becoming more important since the endurance of many new flashes becomes smaller. By inhibiting BG applications, refault-induced I/Os are reduced, which is friendly to the lifetime of the flash storage. Note that many newly published mobile products [37, 39, 40] enabled the storage-based swap function, which reclaims anonymous pages to a flash partition, instead of being compressed to the ZRAM area. In this case, the lifetime advantage of Ice and Ice$^+$ on the flash storage is more significant. Second, more user-experience-sensitive applications appear in mobile devices, such as MR (Mixed Reality) headsets, automotive systems, and IoT (Internet of Things) devices. By reducing the resource waste caused by refault, the user experience can be optimized.

BG activity can cause temperature rise. Once the temperature wall is reached, the DVFS (dynamic voltage and frequency scaling) mechanism will actively reduce the processor frequency, leading to overall performance degradation. Constraining the activity of backend applications can help alleviate the temperature rise. Therefore, in mobile systems that generally support DVFS, Ice has a positive effect on avoiding frequency throttling caused by high temperatures. When frequency throttling occurs, the execution efficiency of the BG process decreases, but their relative activity does not change, so Ice's strategy still applies.

Considering the rapid developments in the field of memory management, many new and advanced technologies have been proposed in this field, such as the adaptive swap mechanism. Since Ice is designed to optimize the memory from the process aspect, it can be compatible with these new memory management strategies without too many modifications in the implementation.

Table 3. Applications Used in the Evaluation

Category	Application
Social Network	Facebook, Skype, Twitter, WeChat, WhatsApp
Multimedia	YouTube, Netflix, TikTok
Mobile Game	Angry Birds, Arena of Valor, PUBG Mobile
Electronic Commerce	Amazon, PayPal, AliPay, eBay, Yelp
Others	Chrome Browser, Camera, Uber, Google Maps

5 Experiment Methodology

5.1 Platform and Workloads

This article evaluates Ice against the original Linux memory/process management schemes and the current solutions in mobile systems. The experiments are performed on two smartphones from different manufacturers: Google Pixel3 and HUAWEI P20, which represent low-end and mid-range devices, respectively. The former is equipped with Qualcomm Snapdragon845 core, 4GB DDR4 RAM, and 64GB eMMC5.1 Flash. Android 10.0 (r41) is deployed on the device. The latter is equipped with a HiSilicon Kirin970 core, 6GB DDR4 RAM, and 64GB UFS2.1 Flash. Android 9.0 is deployed on the device. A recent study shows that today's mobile users often run more than 10 applications [51]. So we pre-install 20 top applications on the platforms to simulate daily usage. As shown in Table 3, the applications involved in all of the evaluations are picked from the most popular ones of various categories on the Android market.

5.2 Evaluated Schemes

Four schemes are evaluated for comparison: LRU [23] + CFS [13], UCSG [65], Acclaim [51], and the proposed Ice:

— *LRU+CFS*: LRU is the default memory management scheme in the Linux kernel. With LRU, the least recently used pages are identified as *inactive* and advised to be reclaimed. CFS (completely fair scheduler) is the scheduler that is currently used in Android-based mobile devices. With this scheduler, FG and BG processes are treated fairly. LRU and CFS manage memory and process, respectively. They are implemented as the baseline for comparison.
— *UCSG*: Unlike the original process scheduling, UCSG declares that the FG application usually dominates the user's attention. It treats FG and BG processes differently and redesigns the priority scheme in process scheduling. With UCSG, processes belonging to the FG application are set with a higher priority.
— *Acclaim*: Acclaim redesigns memory management in mobile systems. It is an FG-aware and size-sensitive reclaiming scheme. With Acclaim, pages belonging to the FG application are avoided to be reclaimed. Instead, pages belonging to the BG application prefer to be reclaimed even if their activity is higher than some of the FG pages. With Acclaim, FG refault was effectively reduced.
— *Ice/Ice*$^+$: This is the proposed scheme. Different from previous approaches, Ice co-designs memory and process management. The goal of Ice is to reduce BG refaults. Furthermore, the user experience is evaluated when performing memory reclaim and process killing with the coordination of Ice$^+$.

5.3 Parameter Configurations

The parameters in the evaluation are listed in Table 4. S^g and S^h represent the size of the ZRAM partition. These two parameters are set as 512MB and 1,024MB. They determine how many

Table 4. Summary of Parameters Used by Ice

Symbols	Semantics	Setting
S^g	Size of the ZRAM partition in a Pixel3 phone	512MB
S^h	Size of the ZRAM partition in a P20 phone	1,024MB
H^g_{wm}	High-watermark in a Pixel3 system	256
H^h_{wm}	High-watermark in a P20 system	1,024
δ	Weight coefficient of the proposed MDT strategy	8.0
Et	Epoch length to thaw an application	1 second

anonymous pages can be reclaimed at the maximum. The high-watermark[5] (H^g_{wm} and H^h_{wm}) of the two smartphones are 256 and 1,024. The weight coefficient δ discussed in Section 4.2.3 is relative to the freezing intensity. This parameter is configured as 8.0 in the evaluation. E_t determines how long an application can run in each freezing epoch. For simplicity, we set this parameter as 1 second by default. The parameters are configurable.

6 Experimental Results and Analysis

This section first shows Ice's effect on the user experience. Based on the results, the low-level metrics (e.g., refault) are employed for analysis (Section 6.1). Furthermore, we study the effect of Ice$^+$ on the user experience (Section 6.2) and its effect on the QoS (quality of service) of BG services (Section 6.3). Finally, the overhead is analyzed (Section 6.4).

6.1 Effect of Ice on the User Experience

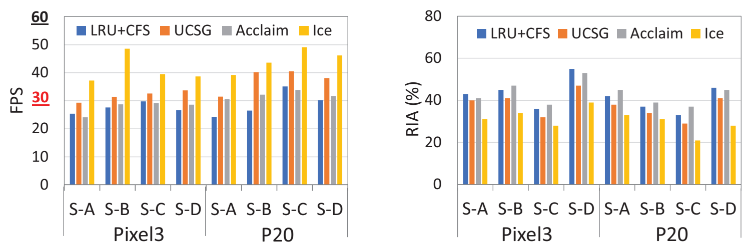
In mobile systems, frame rate and app launching speed are two important metrics of user experience [47]. As mentioned previously, the frame rate can be used to identify whether a user can smoothly interact with the screen, and app launching speed depicts how fast a user's operation can respond.

6.1.1 Benefit on Frame Rate. As discussed in Section 2, it is better to draw more frames per second. In addition, if a frame failed to be rendered within 16.6ms (which is defined as an *interaction alert* by Systrace [20]), the display can become jerky or slow from the users' perspective. This is based on human eye sensitivity [55]. Therefore, we evaluate Ice's benefit on frame rate using two metrics: FPS and RIA (ratio of interaction alert). The metrics are measured in the aforementioned scenarios: video call using WhatsApp, short-form video switching with TikTok, screen scrolling on Facebook, and game playing on PUBG Mobile. Before running these applications, several applications[6] are cached in the BG in advance. Then we run the test application in the FG and record the frame rate using Systrace. To avoid bias, each scenario is tested for 10 rounds and the average is shown. For each evaluated application, we log in with the same user account and conduct a similar sequence of activities for 10 rounds. In each round, we reboot the smartphone and reselect the BG applications from Table 3 randomly. All evaluations are performed with a good Wi-Fi connection.

Figure 9 illustrates that Ice outperforms the other schemes when multiple applications are cached in the BG. For example, when having a video call (S-A) using WhatsApp on Pixel3, the average frame rate with LRU+CFS, UCSG, and Acclaim is 25.4fps, 29.3fps, and 24.1fps, respectively.

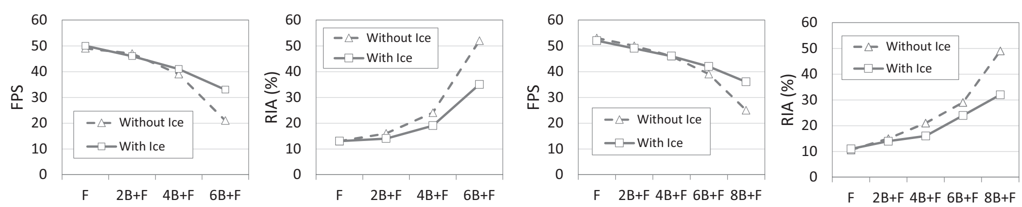
[5]The low-watermark and min-watermark are 5/6 and 2/3 of the high-watermark, which follows the default configuration in the Linux kernel.

[6]There are six BG applications cached in Pixel3 and eight BG applications cached in P20 to fully fill the memory. When caching more applications in the original system, LMK may be triggered.



(a) FPS comparison (b) RIA comparison

Fig. 9. Frame rate comparison in four typical scenarios: video call (S-A), short-video switching (S-B), screen scrolling (S-C), and mobile game (S-D).



(a) Frame rate on Pixel3 (b) Frame rate on P20

Fig. 10. Frame rate comparison with various numbers of applications cached in the BG.

Usually, frame dropping will occur with FPS beneath 30 [56]. So a smooth user experience is affected. For a smoother user experience, especially for frame-sensitive scenarios, like AR/VR [53], a higher FPS is required. We can see that the frame rate boosts to 37.2fps with Ice. The videos and games in the evaluation can be displayed more smoothly and fluently with Ice. In addition to FPS, Ice reduced the RIA. Taking PUBG Mobile as an example, when we play the battle royale game on P20, the RIA is up to 46%. This means that almost half of the frames failed to draw within 16.6ms. This metric was reduced to 28% with Ice. The results prove that BG application-induced frame rate degradation can be effectively alleviated.

UCSG can also improve the frame rate. This is because the priority of BG processes is reduced. However, it does not focus on inhibiting the processes that cause page refault. Meanwhile, the processes with low priority can still be executed. Hence, the benefit is limited. As evaluated, the number of page refaults with UCSG was reduced by 24.4% on average[7] when compared to LRU+CFS. Acclaim aimed at reducing FG instead of BG refaults. In some scenarios, like S-B on P20, Acclaim boosts the frame rate since FG refault is reduced. But in some scenarios, like S-C on Pixel3, the FPS degraded. This is because more pages belonging to BG applications were reclaimed with the FG-aware eviction scheme of Acclaim. As a result, BG refaults have a higher possibility of occurring in some scenarios with Acclaim.

To understand the benefit of Ice, the four scenarios are further evaluated with the different number of applications cached in the BG. The average value of FPS and RIA in the four scenarios are calculated together. As the dashed lines show in Figure 10, the frame rendering performance degraded with more applications cached in the BG. In the "F" and "2B+F" cases, the FPS with and without Ice is similar (the small difference dues to measurement bias). Here, "F" means that no application is cached in the BG, and "2B+F" means that two applications are cached. But the "6B+F" case on Pixel3 and the "8B+F" case on P20 illustrate that the trend of the interference could

[7]The game scenario data is obtained as the average of 10 rounds.

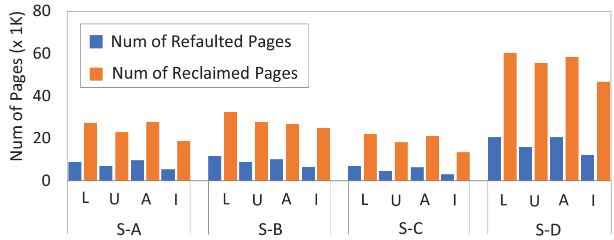


Fig. 11. The number of refaulted and reclaimed pages with LRU+CFS (L), UCSG (U), Acclaim (A), and Ice (I).

be curbed when enabling Ice. Under the two cases, the FPS was enhanced by 1.57x and 1.44x, whereas the RIA was reduced by 32.7% and 34.6%, respectively. Evaluation results suggest that Ice can improve the user experience especially when memory space is almost exhausted by BG applications.

Reduction of Refault and Reclaim. The user experience benefit comes from the refault and reclaim reduction in the BG. To understand Ice's impact on the mobile system, we compare the number of reclaimed pages and the number of refaulted pages in the preceding evaluation. We only show the results on the P20 smartphone because of space limitations. The number of refaults, as well as reclaims in the four scenarios, are evaluated separately. The comparison between LRU+CFS (L) and Ice (I) in Figure 11 indicates that fewer refaults occur with application freezing. As the dark histogram shows, the number of refault pages was reduced by 42.1% in S-A, 44.4% in S-B, 57.6% in S-C, and 40.5% in S-D. In addition, the number of reclaimed pages was reduced. In the evaluation, the identical page may be reclaimed several times due to refault. We add up all of them in the figure. Hence, since Ice reduces refault, the number of reclaim operations in total is reduced too. As the light histogram shows, the number of reclaimed pages with Ice is only 70.7% that of LRU+CFS, on average. The number of reclaimed pages when using PUBG Mobile (S-D) is much higher than in the other three scenarios. This is because the mobile game is memory intensive. As measured, 100MB+ available memory is required to start a new round battle when playing this game. During the evaluation with Ice, only four BG applications on average are frozen. The inactive applications and the active applications that do not cause refault are not frozen by Ice. This demonstrates that Ice can effectively reduce reclaim and refault without needing to aggressively freeze all BG applications.

We can also see that the refault and reclaim reduction of Ice outperforms UCSG (U) and Acclaim (A) in the four scenarios. For UCSG, the refault and reclaim reductions are 51.7% and 53.9% of Ice. For Acclaim, the number of refaults even increased (by 4.3%) in some cases. Hence, we conclude that Ice is effective at reducing both reclaim and refault in the BG.

Note that some commercial smartphones support the process freezing feature in power management, especially on modern high-end devices. We enabled the power-oriented freezing feature on the P20 smartphone and checked its effect on the refault and reclaim in memory management. As shown in Table 5, the power manager with freezing features has a positive impact on reducing refaults. Specifically, the total number of reclaimed and refaulted pages was reduced by 22.4% and 33.5% on average when compared to the LRU+CFS case. The inhibition of refault and reclaim is not as effective as Icebecause the power manager is not designed to dynamically and flexibly tune its freezing opportunity and target with *memory awareness*. For example, the power manager tries to freeze applications even when the memory pressure is low. Still, the freezing intensity is not changed when the memory pressure increases, even when suffering frequent refaults. Meanwhile, we observe that the power manager of some manufacturers' smartphones does not freeze when the device is charging. This design logic is reasonable in power management but is unfriendly

Table 5. Number of Refaulted and Reclaimed Pages (×1K) with Process Freezing (Power Manager vs. Ice)

Scenarios	Power Manager		Ice	
	Refault	Reclaim	Refault	Reclaim
Video Call (S-A)	6.712	20.063	5.233	18.688
Short-Video Switching (S-B)	7.332	26.061	6.457	24.832
Screen Scrolling (S-C)	3.856	15.772	2.929	13.312
Mobile Games (S-D)	14.858	51.433	12.18	46.848

to reducing BG refaults. The proposed Ice is orthogonal to the freezing feature of the power manager.

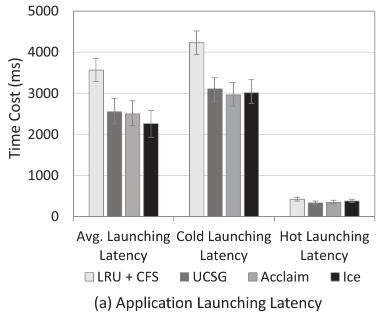
Reduction of I/O and CPU Pressure. The number of I/O requests is counted during the evaluation. It is easy to understand that the I/O size is reduced when active BG applications are frozen when compared to the unfrozen case. For fairness, we count the I/O amount over a long period (10 rounds of evaluation of the four scenarios, 5h+30min in total). During this period, the applications are not only frozen but also thawed with MDT many times. Evaluation results show that Ice did not introduce additional I/Os. Instead, the I/O size was reduced by 9.2% with Icewhen compared to LRU+CFS. During the evaluation without Ice, we find that many file-backed pages are demanded by BG applications, then discarded during reclaim. Then demanded (refault) again. Such senseless I/Os are effectively avoided when enabling Ice.

In addition to the I/O pressure, Ice reduced the CPU pressure. The CPU utilization is 55.8% on average in the LRU+CFS case. This value was reduced to 47.3% with Ice. This shows that the waste of computing resources is effectively alleviated. On one hand, this is because some BG tasks are frozen, which reduces additional CPU consumption. On the other hand, the number of memory compression and decompression tasks decreased.

Whitelist Study. In the preceding evaluation, Ice can identify the critical services (e.g., BG music playback, detailed in Section 6.3) and application priority without depending on the whitelist. If developers add some applications to the whitelist manually, these applications will not be frozen. In the extreme case, we can add all BG applications to the whitelist. In this case, the benefit of Ice degraded since no sufficient set of BG applications for Ice work effectively. To understand the effect of the whitelist, we add all BG applications to the whitelist and repeat the preceding frame rate evaluation. Experimental results show that the FPS in this extreme case is close to the original system (without Ice). Specifically, the average frame rate of video calls on Pixel3 is 25.2fps on average. Ice respects users' operations, even if sacrificing some of the benefits.

6.1.2 Impact on Application Launching. The impact of Ice on application launching is more complicated. On one hand, Ice has a negative impact on launching speed, as it takes time to thaw a frozen application before switching it to the FG. Moreover, when switching a frozen application to the FG, more pages may be demanded in the launching phase. On the other hand, Ice has a positive impact on launching speed since the interference of BG I/Os is alleviated and more CPU cycles can be allocated to the FG tasks. We measure the 20 applications to understand Ice's ultimate impact on launching speed.

We launch the applications for 10 rounds repeatedly. Each application in the FG runs for 30 seconds. Then we switch it to the BG and start up the next one. In the 10-round evaluation, memory was quickly filled, and page reclaim was triggered frequently. Note that some applications in the BG may be killed by Android LMK [44]. This is close to real usage scenarios. During the evaluation, two tools were adopted: Android Debug Bridge (Adb [18]) and UI/Application Exerciser Monkey



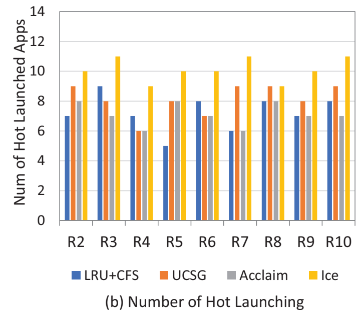


Fig. 12. Impact of Ice on application launching. The results show that Ice's impact on hot launching speed is small and the cold launching speed can be improved (a), and applications could be hot launched when enabling Ice (b).

(Monkey [19]). Adb is a versatile command-line toolkit used to launch applications, identify their launching styles, and record the launching latency. Monkey is adopted to simulate user behaviors. It generates pseudo-random streams of user events, such as clicking, touching, and scrolling. Based on the tools, applications are launched and executed automatically.

Impact on Launching Speed. During application launching, the time cost and launching style are obtained with the command `#adb am start`. Figure 12(a) shows that the average launching time with Ice decreased by 36.6% when compared with LRU+CFS. The launching time is defined as the time span from the time point when a user taps on the shortcut icon of an application to the point the user can interact with the application. This indicates that the positive impact of Ice outperforms the negative impact. To further understand the reason, we analyze the time cost of cold launching and hot launching separately. Also as shown in the figure, it takes 4,237ms on average to cold launch an application with LRU+CFS, whereas the time cost is reduced by 28.8% when enabling Ice. Ice has a positive impact on cold launching, even though it does not accelerate the launching phase directly. With Ice, more resources can be allocated to the launching process and less interference occurs. In addition, the negative impact of application freezing does not apply to the cold-launched application. So the cold launching speed improvement is significant.

The impact of hot launching varies among the applications. As evaluated, 47% of them slow down when enabling Ice. For others, the launching speed was enhanced. This depends on how seriously the applications are affected by BG refaults. The latency increasing of hot launching are smaller than their standard deviations. This suggests that the benefit can offset the penalty in most cases, which is acceptable compared to the user experience benefit earned.

One potential penalty of Ice is that if too many pages of a frozen application were reclaimed, its hot launching speed may be degraded seriously. So we further explore the worst case with Ice. Specifically, we reclaim all pages of an application and freeze this application in the BG manually. Then, we thaw this application and move all required pages back during the launching phase. All pre-installed apps are evaluated in this way. Evaluation results show that the hot launching latency in the worst case is 839ms on average, which is 1.98x of the hot launching latency with LRU+CFS. This demonstrates that Ice may slow down the hot launching speed. But we believe that the worst case is acceptable. On one hand, such cases do not always occur in daily usage. On the other hand, the hot launching speed in the worst case is still much faster than cold launching. Note that this penalty can be further eliminated by using it in combination with application prediction [7, 58]. If a BG application is predicted as the next used application, Ice can thaw it ahead of time. Ice can also run together with launch boosting schemes, like MARS [31] or ASAP [62], to further eliminate the penalty.

Table 6. Frame Rate Improvement Comparison of Ice and Ice$^+$, and Their Effect on the System

		Frame Rate (fps)		Num. of Reclaimed Pages (× 1k)		Num. of Refault Pages (× 1k)	
		Ice	**Ice$^+$**	**Ice**	**Ice$^+$**	**Ice**	**Ice$^+$**
Video Call	Pixel3	37.2	39.1	21.372	16.256	8.737	7.618
	P20	39.2	42.2	18.688	13.375	5.233	5.122
Short-Video Switching	Pixel3	48.6	52.7	19.637	16.254	10.526	8.662
	P20	43.6	45.6	24.832	19.938	6.457	4.434
Screen Scrolling	Pixel3	39.5	41.3	17.618	15.261	5.533	5.006
	P20	49.1	50	13.312	12.127	2.929	3.128
Mobile Games	Pixel3	38.7	40.1	53.761	50.535	18.632	16.736
	P20	46.2	48.7	46.848	41.336	12.18	10.628
Average		42.8	45	27.054	23.135	8.778	7.667
Summary (Ice$^+$: Ice)		**1.05 ↑**		**85.52% ↓**		**87.34%↓**	

Ratio of Hot Launching. The average launching speed is boosted not only due to the reduction of BG interference but also because more applications were hot launched. Figure 12(b) depicts the number of hot-launched applications among the evaluated schemes. As introduced, the applications are repeatedly launched for 10 rounds. In the first round, all applications are cold launched. In the following 9 rounds, several applications are successfully cached and can be hot launched. This figure only shows the hot launching number from round 2 to round 10 because all applications are cold launched in the first round. The results illustrate that the application caching capability with Ice outperforms previous works. In general, only seven or eight applications are cached with LRU+CFS. When enabling Ice, 25% more applications could be hot launched. Ice is friendly to application caching because it alleviates the refault-induced memory pressure. As a result, the possibility of triggering LMK decreased. Meanwhile, the time point to trigger application killing has been delayed. More applications were switched to the FG before being killed.

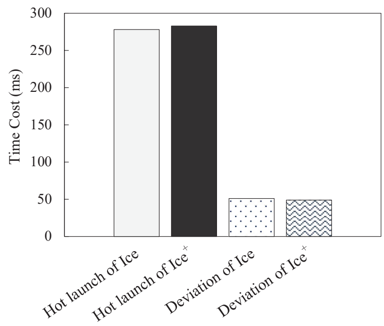
6.2 Effect of Ice$^+$ on the User Experience

In addition to the fundamental freezing function of Ice, this article further evaluates the benefit of Ice$^+$ on the user experience and analyzes its impact on the system. Both frame rate and application launching speed are evaluated when the proposed freezing technique coordinates with existing memory reclaim (ZRAM) and LMK mechanisms. The evaluation method is as mentioned previously.

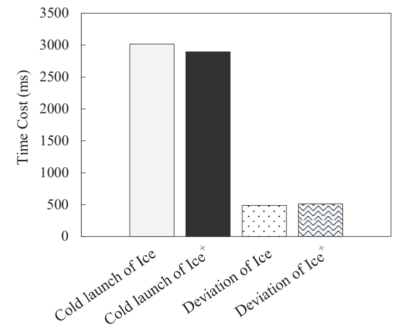
6.2.1 Frame Rate Improvement. Table 6 illustrates that the FPS of the four scenarios can be further enhanced (by 5.14% on average) when Ice coordinates with the original schemes. Taking short-video switching (S-B) as an example, the average frame rate increased by 4.1fps (on Pixel3) and 2fps (on P20) separately.

System Improvement Analysis. To understand Ice$^+$'s effect on the system, we record the number of reclaimed and refault pages during the evaluation. The four scenarios are evaluated separately. Also in Table 6, the number of reclaimed pages under Ice$^+$ is reduced by 14.5% on average. We monitor the ZRAM partition and find that 5.8k reclaimed pages (21.4%) will be released shortly because of LMK in the Ice case. In addition, the total amount of refault is reduced by 12.7% on average when enabling Ice$^+$. This demonstrates that the refault-induced user experience problem can be further addressed when Ice coordinates with ZRAM and LMK.

6.2.2 Impact on App Launching. Ice$^+$ enhances the frame rate by avoiding unnecessary reclaim operations. Whether a page is frozen or not is considered in the LRU algorithm. However, this policy might negatively impact the launch speed, as it takes additional time to maintain the freezing-related information. Thus, we measure the possible loss in the launching speed of different applications. Both cold and hot launching are measured. The average time cost and the



(a) Hot launch comparison



(b) Cold launch comparison

Fig. 13. Average launch latency and the deviation comparison between Ice and Ice$^+$. The results illustrate that the user experience can be further improved when Ice coordinates with existing mechanisms.

standard deviation are shown in Figure 13. For the average time cost, the smaller the value, the better, and the smaller the value, the better for the standard deviation. The results in the figure suggest no noticeable impact: the difference between the mean values of Ice and Ice$^+$ is smaller than their standard deviations.

6.3 QoS of BG Services

The QoS that BG applications provide can be as important as FG applications—for example, people may run audio applications (e.g., music, navigation, and talk[8]) or download-related applications (e.g., delivering file point-to-point, downloading a file through network, and caching TV series) in the BG. To understand whether these BG services are affected by Ice, we evaluate these scenarios separately. For each scenario, six cases are evaluated: Empty-NoIce, Empty-Ice, and Empty-Ice$^+$ mean that we conduct the evaluation without Ice, with Ice, or with Ice$^+$ when no other applications are cached in the BG; differently, Full-NoIce, Full-Ice, and Full-Ice$^+$ means many applications are cached in the BG.

To quantify the smoothness of audio playback (on P20), we use the other device (Pixel3) to record the audio, then we use three metrics derived from time-domain and frequency-domain analysis: **Zero-Crossing Rate (ZCR)**, RMS Amplitude Variation, and Spectral Flux. Each provides different insights into the audio signal's characteristics. Specifically, ZCR measures how often the audio signal changes sign (crosses the zero line). A higher ZCR can indicate noise or abrupt changes, suggesting less smoothness. RMS Variation measures the consistency of the signal's power. Large variations indicate fluctuations in volume, which can signify stuttering or dropouts. Spectral Flux measures the rate of change in the power spectrum. Higher Spectral Flux indicates more sudden changes in the frequency content, which could mean less smooth audio. We developed a tool in the Python language[9] to analyze the preceding metrics. To create an overall smoothness score, we normalize each metric (e.g., ZCR, RMS Variation, Spectral Flux) to a 0-1 scale and take the weighted sum:

$$Smoothness\ Score = w_1 \times (1 - ZCR) + w_2 \times (1 - RMS\ Variation) + w_3 \times (1 - Spectral\ Flux), \quad (2)$$

where w_1, w_2, and w_3 are weights that sum to 1. We say an audio is smoother if its value is a positive number when compared to the baseline. We choose the Empty-NoIce case as the baseline and set the three weights to $\frac{1}{3}$. Now we give an example to show how the smoothness is compared.

[8]We switch the short-form videos to the BG and play them in audio mode.
[9]The *librosa* library is required in the development to support audio analysis.

Table 7. Effect on the BG Services

Scenarios		Empty			Full		
		NoIce	**Ice**	**Ice$^+$**	**NoIce**	**Ice**	**Ice$^+$**
Audio	Music	0.0	−0.0148	−0.0132	0.0	0.0075	0.0139
	Navigation	0.0	−0.0067	0.0114	0.0	0.0236	0.0131
	Talk	0.0	0.0217	−0.0083	0.0	0.0217	0.0193
	User Perceptible	**NO**			**NO**		
Download	Download One File (Mbps)	66.3	65.8	67.1	58.9	59.6	60.2
	Download TV Series (min)	357	355	361	373	368	365

We calculate their smoothness score for audio that played under different cases (e.g., full or empty, with(out) Ice) and compare it with the baseline. For example, in our evaluation, a music's ZCR is 793.5 zero-crossings per second in the Empty-NoIce case, whereas the metric value is 792.8 zero-crossings per second in the Empty-Ice case. The RMS Variation of the music under the preceding two cases are 0.65 ± 0.095 and 0.65 ± 0.097. Their Spectral Flux is 0.083 and 0.085, respectively. Based on Equation (2), we can calculate that the smoothness score of the baseline is $\frac{1}{3} \times (1 - \frac{793.5}{793.5}) + \frac{1}{3} \times (1 - \frac{0.095}{0.095}) + w_3 \times (1 - \frac{0.083}{0.083}) = 0$, and that of the Empty-Ice is $\frac{1}{3} \times (1 - \frac{792.8}{793.5}) + \frac{1}{3} \times (1 - \frac{0.097}{0.095}) + w_3 \times (1 - \frac{0.085}{0.083}) = -0.0148$. This means that the audio smoothness in Empty-Ice (with a score of −0.0148) is lower than the baseline (with a score of 0). However, we repeat each evaluation 10 times and find that the amplitude is within ±1.0 normalized range, which means that Ice's effect on the audio is negligible.

The download efficiency is also monitored. For a given file, we monitored the bandwidth using *wireshark* [27]. In terms of the TV series, we recorded the time cost to download all episodes. The results are detailed in Table 7.

Three phenomena are observed in the evaluation. First, the audio and download services are not stopped due to Ice. Note that these services are not manually included on the whitelist. Android OS can identify them in the framework layer. This proves that by employing the existing Android mechanism, Ice does not freeze the 'critical' BG services. Second, Ice/Ice$^+$'s effect on the smoothness score and downloading performance is negligible compared to the benefit it earns. Third, the smooth scores of music playback of Full-Ice and Full-Ice$^+$ case are 0.0075 and 0.0139, separately. This demonstrates that freezing can even improve the QoS of critical BG services when the BG is busy instead of making them worse.

Considering the user experience is determined by users' subjective feelings, we conducted a user study on six volunteers. Specifically, we play music and ask them to guess whether our scheme is enabled. According to the feedback of the investigation, this article demonstrates that Ice's effect on the service is user imperceptible.

6.4 Overhead Analysis

6.4.1 Memory Consumption. Ice maintains a mapping table, incurring a space overhead in the memory. In the implementation, all applications installed by users are recorded in the mapping table. For a device with 20 installed applications, and each application consisting of three processes, the memory consumption is 13.8KB at maximum, including 20×64B for UID, 20×3×64B for PID, 20×3×1B for freezing state, and 20×3×64B for priority score. Corresponding objects in the mapping table will be deleted if an application's lifecycle ends. In this way, the scale of the mapping table is under control. In addition, we set an upper bound for the mapping table for safety. The upper bound is set to 32KB, which is enough to accommodate the information. In summary, with the optimizations in data structure management, the total memory consumption is at the 10KB level. This is negligible compared to the total memory available on the smartphone.

6.4.2 Performance Overhead. The performance overhead of Ice is broken down into three parts. First, it takes time to respond to the refault events. Specifically, Ice needs to obtain the process information, index the PID, and perform freezing. Ice performs these operations in an asynchronous approach so that the page accessing will not suspend. Second, the UID-PID mapping needs to be maintained. When the system is booted, Ice checks the configure file in Android to obtain the UIDs of the installed applications. The mapping table is initialized when the system is booted and is updated when installing or launching an application. When the lifecycle of an application starts or ends, the process list in the mapping table needs to be updated. Meanwhile, when the freezing state changes, Ice needs to index the corresponding UID and update the corresponding state in the table. Since the table size is small, Ice maintains the table in memory. Thus, one table indexing can be completed at the microsecond level. The time consumption is negligible in comparison with the launching latency. The third part is the freezing-induced performance overhead. As mentioned previously, it takes only tens of milliseconds to thaw an application, which is acceptable compared with the launching time. In addition, Ice conducts a series of optimizations in the design to minimize the penalty. For example, only active applications are allowed to be frozen. The applications having no pages reclaimed, or the applications having pages reclaimed but no refaults, will not be frozen. The overhead is acceptable in comparison with the benefit.

7 Related Work

Memory Management. Many efforts have been made to optimize the memory reclamation schemes [4, 6, 30, 43, 45, 48, 49]. SmartSwap [72] predicts which applications are unlikely to be used and evicts pages from those applications ahead of time. FlashVM [61] focuses on changes to the virtual memory system to make effective use of available fast storage devices for memory reclaim. MARS [31] is designed to speed up application launching through flash-aware swapping. It employs a series of flash-aware techniques to speed up the launching speed. Based on that, SEAL [47] proposed a two-level swapping framework for user experience improvement. These schemes effectively optimize modern mobile systems. However, the proposed BG refault issue has not been well considered. Acclaim [51] focused on the FG application-induced page refault problem. But based on our study, more than 65% page refault still occurs when applications are alive in the BG. The proposed scheme harms BG refault. Marvin [46] found that runtime GC may cause BG refault and proposed a new memory management scheme in language runtime. With Marvin, the GC-induced page refault can be avoided. Fleet was proposed to improve the number of cached apps and hot-launch performance [35]. However, this work has shown that more than 77% of refaults cannot be effectively alleviated in this way. To address this issue, we propose a new freezing approach. Several studies try to aggressively and proactively reclaim dirty pages of BG applications so that it is cheap to find a new page for the FG process when it needs them, like SmartSwap [72] and Marvin [46]. This approach cannot fundamentally address this issue. On one hand, aggressively and proactively reclaiming induces more severe memory thrashing, which means more resource utilization and power consumption. On the other hand, since a large number of early reclaimed pages are refault back, the effectivity of early reclaim is significantly degraded. By coordinating Ice with this early-reclaim-like approach, we believe the efficiency and effectivity of memory reclaim can be further improved.

Process Scheduling. There are several strategies to optimize the process [29, 50, 57, 60, 69, 71]. Chang et al. [5] suggested that the FG process should be differentiated from BG processes because the former usually dominates the user's attention. In the work of Sungju et al. [63], the system identifies user-interactive processes at the framework level and then enables the kernel scheduler to selectively promote the priorities. Priority-based scheduling without aware memory insight cannot address the BG refault issue since there are great differences in the behavior characteristics of BG applications. These applications should be treated differently in terms of the refault factor. Energy managers that shipped with some smartphones support process freezing [16, 38, 54]. However, these features focused on energy saving. They tend to freeze the BG processes that consume a lot of energy, but cannot restrict refaults accurately and timely. There are also some efforts focused on maintaining the performance of interactive applications that are competing with BG tasks [11, 17, 34]. However, to the best of our knowledge, the memory-induced scheduling issue has not been fully addressed. By coordinating memory and process management, Ice significantly improves the user experience at the system level.

8 Conclusion

This article aimed to improve the user experience of resource-limited mobile devices and proposed Ice. Through selective BG process freezing, the BG page refault issue can be effectively alleviated in memory management. To realize Ice, two schemes were proposed: RPF and MDT. Ice can be implemented on smartphones with no invasive modification in mobile applications and hardware infrastructure. Moreover, this work showed that the refault can be further reduced by coordinating Ice with existing mechanisms in mobile systems, which is called *Ice*$^{+}$ in this article. We have implemented Ice and Ice^{+} on real mobile phones. Experimental results showed that the user experience can be significantly improved with Ice. Specifically, Ice boosts the frame rate per second by 1.57x on average compared to the state of the art. In addition, the frame rate is further enhanced by 5.14% on average with Ice^{+}.

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