Degrading Data to Save the Planet

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ABSTRACT

Storage capacity demand is projected to grow exponentially in the coming decade and so will its contribution to the overall carbon footprint of computing devices. In recent years, cloud providers and device vendors have substantially reduced their carbon impact through improved power consumption and product distribution. However, by 2030, the manufacturing of flash-based storage devices will account for 1.7% of carbon emissions in the world. Therefore, reducing production-related carbon emissions of storage is key to sustainability in computing devices.

We present Sustainability-Oriented Storage (SOS), a new host-device co-design for personal storage devices, which opportunistically improves storage sustainability by: (1) targeting widely-produced flash-based personal storage devices; (2) reducing hardware production through optimizing bit density in existing materials, up to 50%; and (3) exploiting an underutilized gap between the effective lifespan of personal devices and longer lifespan of their underlying flash.

SOS automatically stores low-priority files, occupying most personal storage capacities, on high-density flash memories, currently designated for nearline storage. To avoid data loss, low-priority files are allowed to slightly degrade in quality over time. Switching to high-density memories, which maximize production material utilization, reduces the overall carbon footprint of personal storage devices.

CCS CONCEPTS

• **Hardware → Impact on the environment**.

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1 INTRODUCTION

The changes in Earth's climate pose an enormous challenge for all sectors of society. The environmental impact, or carbon footprint, of devices includes carbon emissions during a device's major lifecycle phases [1, 2]: (1) material procurement; (2) manufacturing; (3) product dissemination; (4) operational power consumption; and (5) eventual disposal. Specifically for computing devices, their permeation to every aspect of human life presents a challenge in creating more sustainable environments.

Computer system designers have worked diligently over the years to optimize performance, power-consumption, and costs of devices during operation. To wit, recent analyses show that power consumption during systems operational phase has significantly improved [3–5]. In addition, vendors have laboriously worked to make other phases of a device's lifecycle, such as packaging and material procurement, more sustainable [6, 7]. As a result, production-related emissions effectively account for most of the carbon footprint of modern devices and datacenters [3, 4, 8]. However, computing systems already optimize by minimizing hardware requirements. Thus, directly reducing systems environmental impact *without* producing less hardware poses a unique

In this work, we focus on storage and its contribution to the overall environmental impact of systems. We specifically target flash-based storage, because it comprises a significant portion of the total carbon footprint of computing systems. For example, flash storage alone is responsible for up to 12-31% of iPhone14's carbon footprint [9] and SSDs comprise 33-80% of a computer's carbon footprint [8]. At a higher level, flash is poised to soon become the dominant storage medium [10] as flash annual capacity production in 2021 reached a staggering ~765 Exabytes [11]. Based on a recent analysis [8], the associated flash production-related carbon emissions were ~122M metric tonnes of CO2, equivalent to the average annual CO2 emissions of 28M people [12]. By 2030, this figure will have reached the equivalent of over 150M people [10, 13], an exponential growth which must trigger development of new, more sustainable designs.

We identify an opportunity to improve the overall carbon footprint of flash-based personal storage devices (e.g., mobile). Our solution is derived from two observations. First,

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most flash production is used for personal devices which are discarded (and never re-used) long before their on-board storage device is worn-out (§2). Second, the carbon footprint of flash production will heavily increase in the coming decade as flash density improvements are projected to significantly lag behind the increasing growth in demand (§3).

We propose Sustainability-Oriented Storage (SOS), a new design for leaner personal flash-based storage devices (§4). SOS combines several SSD management techniques and flash technologies to effectively increase device sustainability without hampering usability. Namely, we propose: (1) to shift all personal storage to low-endurance, denser memories for the same capacity; (2) to use a machine-based mechanism to automatically detect low-priority, read-dominant, error-tolerant files and place them on lossy memories; (3) to store most personal data (i.e., media files) using approximate storage techniques that slightly degrade data integrity while retaining sufficient quality; and (4) to introduce capacity variance by gracefully re-using, and finally retiring, worn-out blocks.

Solutions using extremely dense memories have recently become commercially viable for nearline storage workloads [14]. Still, personal storage devices use less dense flash memories [15, 16]. We propose a design that switches personal storage devices to denser memories, which enable up to 50% more bits for the same amount of cells. By using denser flash memories, SOS straightforwardly optimizes material utilization, which proportionally reduces the associated carbon footprint for the same storage capacity.

This optimization utilizes an existing gap between the expected lifetime of personal computing devices and the larger resilience of their underlying flash devices. The gap is sufficiently large as to be utilized for increasing device sustainability. The design of SOS satisfies users needs (e.g., media consumption) on personal devices by selectively degrading data without prematurely wearing out low-endurance flash before the encasing device is discarded.

The design of SOS follows recently advocated directions for more sustainable systems [3]. Adhering to sustainability-oriented design principles means that systems designers must revise OS mechanisms and policies, which are currently optimized to other goals. SOS is one of several such first steps necessary to improve the sustainability of future systems.

2 MOTIVATION

2.1 Background

Flash stores data by electrically charging cells to predefined voltage thresholds. Corresponding logical values (e.g., 0/1) are determined by measuring and comparing each cell voltage to predetermined read reference voltages. Cells can store more bits using more precise, slower, programming process which differentiates between smaller voltage level ranges.

Reading and writing data is done at page granularity, typically 4-16 KB in size, by further charging cells in the relevant page. Rewriting a page requires a slow "erase" operation to uncharge cells. Erasures are performed in the granularity of *blocks*, groups of pages typically 256-4096 KB in size.

Cells can typically endure 1–5K program/erase cycles (PEC) before they wear out and can no longer reliably store data. To maintain minimal endurance levels, programmed data is encoded with error-correcting codes (ECC).. SSD controllers regularly move data between blocks to ensure even wear levels and avoid data loss due to premature wear out.

2.2 Density and Flash Lifetime

Flash memories are produced from large ultra-thin silicon wafers using advanced lithography and etching processes. Several techniques have been successfully employed over the years to improve flash density.

First, lithography improvements dramatically reduced flash cell sizes from 300nm to around 15nm [17, 18]. Such *lateral* scaling allowed vendors to place more cells onto the same physical layout. Second, *logical* scaling of bit density has also increased. Single-level (SLC) and multi-level (MLC) cells, storing one and two bits per cell correspondingly, dominated the flash market a decade ago. Nowadays, most modern SSDs use denser three-level (TLC) and quad-level (QLC) cells [19] and vendors are expected to start producing penta-level cells (PLC) SSDs soon [14]. Third, in the past flash vendors used a 2D process to produce flash cells. However, in recent years vendors have widely adopted a 3D cell layer architecture [20] by *vertically* overlaying cells who share logic components.

The aforementioned density improvements significantly reduce flash prices by more efficiently utilizing raw flash memory wafers used in the production process and reducing flash media geometry. However, downsides include increased electrical disturbances due to smaller cell sizes, impacting reliability and endurance [21]. Increasing bit density has also reduced flash endurance from ~100K PEC for early-generation SLC memories to ~1K PEC for QLC memory [22].

Flash cell technology has reached its 2D geometric limitations. Consequently, layer stacking remains the main hardware scaling and cost reduction technique for flash. In recent years vendors have consistently increased the number of cell layers in flash packages to over 200 [17, 23]. This trend is expected to continue in the near future. For instance, Samsung projects achieving flash packages with over 1K layers [24] by 2030, effectively quadrupling current storage densities. Notably, although 3D flash architecture introduces some new reliability and endurance effects [25] it allows vendors to use larger-size cells, which are less susceptible to electrical disturbances and more endurant [26–28].

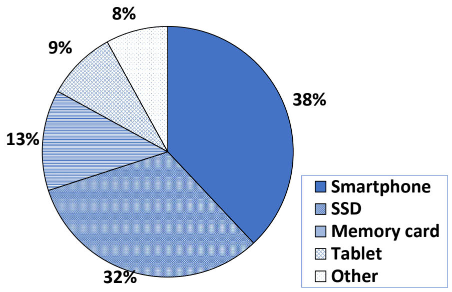

Figure 1: Flash market share by device type (2020).

2.3 Flash Utilization

Utilizing flash and flash-based storage devices for longer periods of time decreases demand for producing more flash in order to replace old media and devices. In this section we examine the factors affecting flash media utilization.

2.3.1 Flash Wear-out. The first factor we must consider is wear out of underlying flash packages. Most SSDs nowadays use either TLC or QLC flash, whose cells can endure a few thousand write cycles at most before being considered worn out. However, a closer look at lifetime warranties of flash-based storage devices shows that they are quite long for typical use cases with common lifetime warranties of five years [29, 30]. The literature shows that even under relatively stressful use in enterprise settings wear out of the underlying flash packages is a minor cause for drive failure [31, 32]. Memory cards common warranty periods are longer, typically 5–10 years [33, 34]. Mobile devices typical warranties are 1–2 years [35–37]. Consequently, mobile storage device lifetime typically outlasts the encasing mobile system [38]. These figures reflect vendor estimates that most end users and applications rarely re-write their entire devices frequently as to wear out the underlying flash media. Therefore, we conclude that **flash wear is a relatively minor factor in determining the effective lifetime of modern flash-based devices**. Thus, extending flash device lifetime to increase sustainability [2] is not beneficial.

2.3.2 Replacement rate. The second factor is the replacement rate of the encasing device, i.e. SSDs and embedded/mobile systems. To understand the implications and suitability for users needs we take a closer look at the flash storage market.

Figure 1 illustrates a recent overview [39] of the target devices for flash bit manufacturing. The figure shows that full-fledged SSDs (enterprise and consumer) comprise only 32% of the yearly flash bit production. Several studies in recent years have examined the failure rates of SSDs in enterprise settings [31, 32, 40] indicating low annual SSD failure rates of $\sim 1\%$. Although these numbers refer mostly to enterprise settings we assume that the failure rates of SSDs in less demanding consumer setups follow a similar trend.

We observe that a prominent use case for flash storage is *personal storage devices* (phone and tablet), comprising approximately half of the yearly flash bit production. Notably, the average smartphone use life is two to three years [41–43] and most phone warranties are even shorter (§2.3.1). However, mobile storage wear out analysis [38] shows that, under typical usage patterns, users only wear out a fraction (e.g., 5%) of the total wear phones can endure during their warranty period. Furthermore, most write-intensive apps are unlikely to be utilized for remotely long enough periods (e.g., playing Final Fantasy for 9 hours daily) as to prematurely wear out the underlying storage. The result is that currently used personal storage flash likely significantly outlasts the lifetime of its encasing device by an order of magnitude. Therefore, we conclude that **over half of all flash bits manufactured annually will be discarded and replaced over three times in the coming decade**.

2.3.3 Device Re-use. Flash costs are an important factor in SSDs. Consequently, re-use of flash packages can result in significant savings in production costs. Nevertheless, flash packages are almost never re-used for several reasons.

First, enterprise storage providers generally prefer to shred old devices for security and privacy concerns [44]. Second, the dominant target for flash production is mobile and consumer devices where flash chips are soldered onto the platform board [38]. Whenever a mobile device is discarded, the on-board flash is also discarded. Recycling mobile storage devices to reduce their carbon impact requires incorporating re-used flash packages of different models and age into the same device [8], which may prove technically challenging and a deterrent for both vendors and users.

Third, old mobile devices are typically not re-used [43] due to lack of demand and saving old phones for backup. Recycling flash packages requires an expansive infrastructure for collecting, de-soldering, formatting, quality-checking, disseminating, and re-soldering re-used packages. Establishing and maintaining such an infrastructure is likely a difficult and lengthy task. Finally, efforts to modularize mobile platforms have not been successful [45] or do not include modular storage components[46]. Thus, we conclude that **re-using flash packages will likely not become a sustainable alternative for flash production in the foreseeable future**.

Technology alternatives. SSDs are poised to slowly overtake HDDs as the main technology for non-archival storage in coming years. Furthermore, since flash production nowadays is geared towards mobile devices, flash is the dominant worldwide storage medium nowadays.

Multiple promising NVM technologies have been proposed as potential alternatives to flash [47, 48]. Unfortunately, none of the proposed technologies is currently commercially viable and scalable. Most prominently, the recent implosion of Intel's 3D XPoint Optane [49], the most mature of these alternatives, means that **flash will likely remain the dominant storage medium in the coming years**.

3 CARBON FOOTPRINT OF FLASH

Several works in the literature have analyzed the carbon emissions impact of flash manufacturing over the years. Boyd et al. [50] performed a comprehensive life-cycle analysis of NAND flash for earlier generation packages. More recently, several works performed an extensive review of the life-cycle impact of flash [5] and SSDs [8]. The results show that most related emissions are due to power consumption from non-renewable sources of energy (i.e., coal and gas) during the flash die manufacturing process. Unfortunately, constructing new renewable sources of energy is a lengthy process which can take years. East-Asian countries, the location of most global flash production [51], plan to switch only partially to renewable energy sources by the end of the decade [52–54]. We conclude that **flash production-related carbon emissions will continue to overshadow any gains in operational power consumption in the coming decade**.

Furthermore, projections indicate ~20-30% annual growth in the global data volume [55, 56]. Flash capacity production is projected to increase correspondingly [11] or even further [13, 57]. Flash vendors assert they will quadruple output capacity within a decade (§2.2) by more efficiently utilizing materials (due to vertical layer stacking). Therefore, improvements in flash density alone may be roughly equivalent to the increase in demand for data storage.

However, the share of flash-based storage in overall storage sales is expected to significantly rise as SSDs continue to overtake slower HDDs in cloud and enterprise environments [13, 58] and users increasingly switch to high-capacity smartphones [59]. The frequent replacement rate of personal devices (See §2.3) will only exacerbate demand for more flash production. We therefore conclude that **flash bit production will have to expand significantly beyond the industry's projected growth in flash density**. This expansion will in turn substantially increase the overall carbon footprint of flash storage.

Finally, we consider the role of emissions-related costs for flash storage. CO2 emissions by industry are increasingly taxed through carbon credit schemes where manufacturers must compensate for their related emissions [60], e.g. European Union prices have recently peaked at $111/CO2e ton and are expected to continue rising [61]. Most flash manufacturing is currently located in countries with nascent, cheaper, carbon credit schemes [62, 63], effectively absolving flash production from pollution-related costs. Eventually, these countries will likely increase carbon credit costs to more realistic levels[64]. Coupled with the continuous drop of flash prices we conclude that **carbon-related direct costs may soon become a major factor in the flash storage market**. For example, QLC SSD prices have recently gone as low as 45$/TB [65]. At current levels the aforementioned EU carbon credits would comprise a 40% price increase (assuming 0.16 CO2e Kg per 1GB [8]).

4 EFFECTIVELY USING FLASH STORAGE

4.1 Capacity and Density Tradeoff

To use flash more efficiently we propose to focus on solutions that stave off demand for more flash production. Compromising on device capacities straightforwardly curbs the carbon emissions of storage but substantially reduces its utility. Instead, we propose to optimize production efficiency for the same capacity. For enterprise storage providers restrictions on the rate of new data production, storage capacity, or performance require dramatic changes in their business model, changes which are societally and economically difficult to implement. Personal data on the other hand constitutes the target of most flash bit production nowadays and can be more easily curtailed. Furthermore, data in such devices is more malleable in nature, since it is mostly composed of unstructured data of varying types and importance [66–68] (e.g., media files). We therefore focus on unstructured data in personal storage, i.e. consumer and mobile devices.

SOS wholly adopts denser flash memories in personal storage devices. We propose replacing currently used TLC for a split PLC/pesudo-QLC scheme. Improving TLC density by 33% (QLC) and 66% (PLC) yields 50% improvement in density for the same capacity. This in turn utilizes raw materials more efficiently and increases flash sustainability accordingly.

Switching to high-density memories trades flash device lifetime for increased sustainability. Endurance of early PLC generations will likely reduce by almost a factor of 6-10 versus TLC [22], and a factor of 2 versus QLC. However, switching to low-grade flash should not necessarily cause premature storage device wear out as even the lifespan of existing TLC flash memories exceeds that of personal devices under typical user workloads by an order of magnitude (§2.3). Nevertheless, to further minimize the likelihood of data loss due to premature PLC wear SOS uses data degradation in capacity-restrained low-endurance devices through a combination of several mechanisms, which we now detail.

4.2 Selective Data Degradation

We propose a lean co-design of the storage device and host system to facilitate an intra-SSD hierarchical data management scheme for personal devices. Data is classified according to two factors (1) system functionality; and (2) user preferences. Our solution uses a machine-learning based file classifier (See §4.4) to arrange data according to two sets.

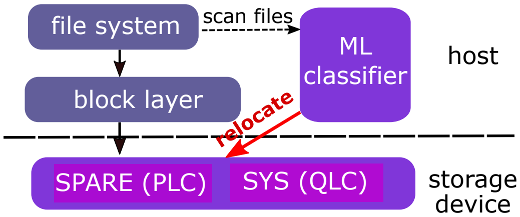

Figure 2: Design of SOS. A machine-learning mechanism periodically detects low-priority file data, which the device then moves to PLC memory.

The first set (SYS) stores *system files* related to the operating system, application metadata, libraries and executables and other files related to core functionality of the device. We further include critical personal information such as documents and media files with personal significance. The second set (SPARE) includes data classified as non-critical and read-dominant, which we expect to include mainly media content of relatively low significance to the user.

The device partitions the physical flash storage space into two physically separate sets of flash blocks with different data management decisions. The first set stores SYS files data which cannot be compromised. Therefore, these blocks are stored conservatively with additional redundancy (e.g, parity) on flash blocks with decreased density to ensure their reliability and integrity, i.e. pseudo-QLC [69].

The second set of flash blocks stores data of reduced importance for which users tolerate some degradation. To ameliorate the low endurance of the underlying flash media, these blocks are managed using approximate storage [70, 71]. In this scheme data is stored with weak protection (e.g., no ECC) assuming that applications can tolerate the implications of increased error rates over time (due to retention and endurance errors). For example, error-tolerant frames, which compose most data in MPEG files, can be approximately stored over flash with low quality loss while significantly increasing flash lifetime [72]. Notably, media files comprise over half of mobile storage data [66–68] and are rarely updated. Therefore, we expect that the low-endurance of PLC flash used for the SPARE block set will suffice for the read-dominant, update-infrequent nature of stored files as most writes will be directed at files stored on high-endurance flash.

Nevertheless, we acknowledge that files of *personal significance* should be managed with stricter guarantees. Therefore, straightforwardly classifying files of certain types (i.e., media) as non-critical according to type is insufficient. Consequently, SOS uses machine-based classification to minimize risking files of personal value. However, we believe most media files on personal devices are not of high value to users and may be identified as such with high probability. We therefore expect most media files to be categorized to the SPARE partition and slightly degraded over PLC flash. Conservatively assuming each partition takes up about half of the device storage, SOS would result in a 50% and 10% capacity gain over using TLC or QLC memory, correspondingly.

We will further investigate adjustments to existing file systems and applications to allow additional file formats to be stored approximately, in order to increase the applicability of SOS.. For example, a bank app is likely less tolerant to degradation in its related files than a social media app.

4.3 Flexible Flash Management

Approximate storage extends the lifespan of relevant flash blocks. However, some low-endurance PLC blocks may still excessively wear due to accumulated read, write, and retention errors. Therefore, such form of storage increases the risk of data loss. The SOS data classification mechanism will strive to minimize critical data loss due to being stored on such high-risk blocks by erring on the side of caution. Moreover, since data in the SPARE partition is infrequently updated severe data degradation will likely be extremely rare in SOS. Finally, we note that currently many users backup data from personal devices in the cloud (often stored in "cold" storage over HDDs). SOS can opportunistically take advantage of such backups by amending overly degraded local data copies through a cloud-backed copy. However, SOS does not inherently rely on the existence of such redundant copies.

Nevertheless, to address this eventuality SOS takes several measures. First, SOS relies on auto-delete data classifiers (See §4.5), which can predict user file deletion decisions with high accuracy (e.g., 79% [68]). Second, preemptively moving data to reduce wear variance between blocks is disabled on the SPARE partition since it effectively shortens overall block lifetime [73]. On the other hand, whenever possible, SOS preemptively moves data whose quality is dangerously degraded from worn-out blocks, which can no longer reliably store data. SOS will then mark worn-out zones/segments as unusable. Consequently, the capacity of the device may eventually slowly reduce and the host file system will be modified accordingly to tolerate capacity-variance [74]. Notably, the UFS mobile storage device standard, used in many Android phones, already supports optional LUNs with varying reliability during power failures as well as dynamic device capacity to extend device lifetime [75]. We further propose to flexibly resuscitate worn-out PLC blocks with reduced density [76], e.g. pseudo-TLC.

Technically, classification information is sent to the storage device for each stored data block. Managing data of different classes may be performed solely by firmware using LBA hints from the host. Alternatively, the device can manage data cooperatively with the host OS through SSD-specific abstractions, such as multi-stream [77] or zoned [78] interfaces, where the host is responsible for placing data blocks in relevant streams/zones with different managements policies.

4.4 Machine-driven Data Classification

As the volume and number of files grow on users devices and remote storage services, managing them becomes difficult. For example, the Samsung S22 device has up to 1TB capacity, which can potentially store over 250K images. Manually managing such volumes of data is not feasible for most users.

To efficiently manage personal storage spaces with minimal manual interference SOS employs a machine-learning based classifier to identify and automatically transition files to lower quality storage. The mechanism operates in the background as a privileged system daemon, which performs a periodic review (e.g., daily) of new file data.

For training, the classifier will use data collected from a large pool of previously scanned users files. Identification of critical system data can be performed by experts according to name conventions, file locations, and file content. For example, OS files are easily identifiable as critical to device operation. As for user-generated data, user files are prioritized according to significance and tolerance for varying levels of data degradation. For example, old videos with work colleagues can usually be classified as low-priority.

Generally speaking, determining priority of media files likely requires inspecting visual elements to determine significance using known traits (e.g., sensitive photos, family members). For other file types, such as documents, classification will similarly rely on file attributes [68], as well as known keywords in content. We plan to periodically re-evaluate user preferences as these tend to change over time [68, 79]. We will further investigate ways to partially integrate user input into the classification process without burdening users with frequent manual file inspection (e.g., prompting users for general preferences on device setup).

Technically, we propose that new file data will first be written to high-endurance pseudo-QLC memory. Once the classifier processes a file's data and deems some of the data as non-critical, the classifier instructs the storage device to move relevant low-priority data to PLC memory. As updates to low-priority data are expected to be infrequent by definition we believe the additional write overhead to pseudo-QLC memory is tolerable. Figure 2 illustrates the design of SOS.

4.5 Implications

Data loss. Under exceptionally write-intensive workloads some PLC flash blocks may prematurely wear out, forcing SOS to trim the amount of data stored on the device to retain functionality. In this case SOS temporarily transforms its data degradation scheme to automatically *delete* data by adapting existing schemes for cloud storage or proposing deletion recommendations to users[68, 79, 80]. Either way, once enough space (e.g. 3% of capacity) has been freed, SOS will return to perform regular data degradation only.

Performance. PLC access speeds will likely be worse than those of less dense memories. However, the performance and endurance of recent QLC generations matches that of early generation TLC memories [81]. Consequently, QLC may also be introduced in mobile and enterprise setups [16, 82]. SOS uses PLC to store low-priority data, mostly accessed using large sequential reads for which personal storage devices perform well [38]. Existing PLC SSDs are designated for similarly sequentially-accessed nearline storage [14]. Furthermore, SOS introduces error tolerance for degraded data which can further reduce read times. We therefore conclude that PLC access speeds will likely suffice to the needs of SOS.

Security. Successful classification requires preliminary training on datasets collected from as many users as possible. However, state-of-the-art shows that user behaviors with regards to potential data loss by automatic curating can significantly vary [80]. Consequently, to optimally manage users data SOS must continuously track and monitor user behavior and file content (e.g., family photos). Many users may deem such tracking as too invasive. We plan to investigate the effect of less-pervasive tracking of user behavior on the accuracy of our proposed data management mechanism.

5 RELATED WORK

Data reduction methods (e.g., compression) often used in enterprise storage are less effective in personal storage [66, 67, 83–85]. Alternatively, moving data from underutilized personal flash devices to shared storage [8] is costly and requires high-speed, high-availability mobile network infrastructure.

Others proposed improving sustainability by moving data between different types of devices (i.e., HDDs and SSDs) to optimize the carbon emissions of systems and workloads [8, 86]. However, such solutions are mostly applicable to shared and enterprise storage (e.g., cloud).

Several studies [87–89] have investigated re-purposing of old smartphones by grouping them into small computing clusters. This approach offers a sustainable, energy-efficient, and cost-effective alternative to conventional server-based cloud computing nodes. However, the commercial potential of these solutions is unclear due to their inferior performance, as well as reliance on faulty hardware.

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