Security and Forensics–Is Solid State Drive a Friend or a Foe?

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Abstract

This paper examines the security and forensic implications of Solid State Drives (SSDs), emphasizing how their architectural complexity enables both covert channels and active attacks. We survey methods for covert storage—such as data remanence in over-provisioned space, FTL manipulation, and analog-state exploitation—as well as timing channels that exploit performance modulation. We also analyze active threats, including firmware-based device impersonation and DMA-level exploits over NVMe. However, beyond these risks, SSDs also introduce underappreciated or unintended security and forensic advantages. Features such as built-in hardware encryption, rapid secure erase, the absence of residual magnetism, and inherent resistance to certain physical side-channel attacks offer meaningful benefits in defensive contexts. These advantages, while not always designed with security as the primary goal, can be leveraged to improve data confidentiality, integrity, and forensic reliability.

As SSD technologies continue to evolve—and with them, emerging paradigms like ReRAM and MRAM—the answer to the question "Is SSD a friend or a foe?" lies not in the medium itself, but in how its capabilities are harnessed—or weaponized—by both attackers and defenders.

CCS Concepts

• **Applied computing → Computer forensics**; **Evidence collection, storage and analysis**; **Data recovery**; **System forensics**; *Cyberwarfare*; • **Computer systems organization → Firmware**; • **Hardware → Post-manufacture validation and debug**; **Power and thermal analysis**; • **Security and privacy → Embedded systems security**; **Hardware security implementation**; **Hardware reverse engineering**; **Malicious design modifications**; **Side-channel analysis and countermeasures**; **Malware and its mitigation**; *Database and storage security*.

Keywords

Covert Channels, Covert Storage Channel, Covert Timing Channel, Firmware Security, Information Hiding, NAND Flash, NVMe, Side Channel, SSD, SSD Forensics, SSD Security, SSD Steganography.

1 Introduction

This paper examines the evolving role of Solid State Drives (SSDs) in information security, highlighting their dual identity as both enablers of secure data protection and impediments to digital forensics. This duality stems from two core aspects of modern SSDs: the complex behavior of NAND flash memory, and the powerful system-level access granted through the PCIe (Peripheral Component Interconnect Express) interface.

NAND-based storage requires sophisticated internal management mechanisms such as *wear leveling*, *garbage collection*, and *over-provisioning*. These features enhance security by supporting data sanitization, resilience to physical degradation, and sometimes hardware-level encryption. However, these same mechanisms hinder forensic efforts by fragmenting, relocating, or irreversibly erasing data in ways that are opaque to forensic tools.

At the same time, the transition from traditional SATA (Serial Advanced Technology Attachment) interfaces with AHCI (Advanced Host Controller Interface) protocols to high-speed NVMe (Non-Volatile Memory Express) protocols over PCIe has elevated the SSD's system privileges—enabling not just performance gains, but also a new class of firmware-level threats. SSDs are no longer passive storage devices; they can actively participate in attacks through malicious firmware, covert data channels, or even device impersonation.

This paper surveys both aspects of the SSD threat landscape. We review recent advances in exploiting internal SSD operations for covert storage and anti-forensics, as well as emerging risks from active, controller-level attacks. In doing so, we argue that SSDs are no longer neutral components in system security but are dynamic entities that must be explicitly addressed in both defensive and forensic strategies.

1.1 The SSD as a Security Ally

SSDs are widely adopted for their performance and reliability, but they also offer substantial security advantages—many of which are underappreciated. Beyond speed and durability, SSDs enable stronger privacy, encryption, and resilience against both software-based threats and physical tampering. Whether deployed in secure enterprise environments, low-resource tactical systems, or forward-operating scenarios, SSDs support modern computing platforms in operating securely under pressure.

One of the most impactful features is hardware-based full-disk encryption (FDE), commonly using standards like AES-256. This encryption is active by default in many SSDs and imposes negligible performance overhead, ensuring that data at rest remains protected even if the device is lost or stolen. Another core benefit is the interplay of the TRIM command and garbage collection. When a file is deleted, TRIM marks its blocks as invalid, and garbage collection later erases them—often during idle cycles. This process reduces data remanence, supports efficient sanitization, and complicates post-deletion forensic recovery. In addition, SSDs inherently resist side-channel attacks, magnetic remanence techniques, and write-hole vulnerabilities—owing to their architecture, wear-leveling behavior, and, in some models, built-in power loss protection and self-destruct mechanisms.

A detailed breakdown of these security properties—including examples, implications, and anti-forensic consequences—is presented in Appendix A.

Table 1: Forensic accessibility: HDD vs. SSD

Feature	HDDs	SSDs
Logical-to-Physical Mapping	Static and transparent	Dynamic and opaque (via FTL)
Access to Physical Media	Direct via sector addressing	Abstracted by controller; raw access restricted
Idle-State Behavior	Inactive when idle	Active (e.g., garbage collection, wear leveling)
Firmware Openness	Often standardized and accessible	Proprietary; vendor-specific and opaque
Repeatability and Data Integrity	High; predictable data behavior	Challenged by autonomous processes and wear

1.2 The SSD as a Forensic Obstacle

SSDs introduce fundamental challenges for digital forensic investigations due to architectural features designed for performance, durability, and security [4, 5, 24, 25, 29, 34]. The most profound challenge in SSD forensics stems from a single, fundamental difference from hard sisk drives (HDDs): the lack of direct, predictable access to the physical storage media. Unlike traditional HDDs, SSDs abstract physical storage behind complex firmware mechanisms—including wear leveling, over-provisioning, TRIM, and garbage collection [37, 38, 67]—which dynamically alter or erase data in ways that undermine standard forensic methods. Below are five key forensics challenges that arise directly from this lack of access to the physical storage layer, also summarized in Table 1.

1.2.1 Absence of Direct Logical-to-Physical Mapping. In HDDs, logical block addresses (LBAs) correspond to fixed physical sectors, allowing investigators to correlate file system metadata with specific disk locations. By contrast, SSDs rely on the Flash Translation Layer (FTL), a firmware-managed indirection layer that continually remaps LBAs to physical flash pages as part of wear leveling [37]. This dynamic remapping prevents forensic analysts from tracing the physical history or layout of data, complicating both timeline reconstruction and spatial analysis of file artifacts.

1.2.2 Inaccessibility of Raw Physical Storage. SSDs also restrict access to unallocated, remapped, or over-provisioned blocks, which may contain remnants of deleted or previous data [29, 38]. Traditional forensic imaging tools, which rely on raw sector access, are unable to capture data stored in these hidden regions and may go undetected without invasive techniques (e.g., chip-off extraction or controller bypass). This limitation has led to proposals for alternative acquisition strategies, such as black-box testing [6], but these remain incomplete or inconsistently applicable. Bonetti et al. [6] proposed a test-driven methodology to evaluate SSD behavior, generating forensic decision trees that help analysts determine whether destructive memory acquisition is necessary.

1.2.3 Autonomous Background Operations. Unlike HDDs, SSDs perform internal housekeeping tasks—such as garbage collection and block erasure—even while idle or disconnected from the host system [6]. These operations can alter or permanently remove data before forensic acquisition occurs. TRIM commands, for instance, immediately invalidate deleted data, and subsequent garbage collection may physically erase the affected blocks [19, 22, 23, 26, 39].

1.2.4 Firmware Opacity and Vendor Lock-In. Another forensic barrier is the proprietary nature of SSD firmware and its FTL implementation. Most modern SSDs, particularly NVMe models, employ undocumented controller logic, making low-level access infeasible without invasive methods such as chip-off analysis [19, 45]. There is no universal method for bypassing controller logic or accessing raw NAND data, severely limiting forensic tool compatibility and requiring specialized reverse-engineering skills. Even advanced techniques often rely on guesswork or heuristics to infer internal behavior.

1.2.5 Obstacles to Repeatability and Integrity. Because of the above factors, SSD imaging lacks the consistency achievable with HDDs. Wear leveling and background processes may yield non-deterministic results across repeated acquisitions. Riadi et al. [48] demonstrated that system-locking software like *Deep Freeze* and *Shadow Defender* can partially preserve drive state, but recovery rates from "frozen" SSDs vary between 60–76%, illustrating the fragility of evidence under these conditions. This autonomous behavior fundamentally undermines the forensic principles of repeatability and integrity, as a truly static and verifiable evidence state is often unattainable.

2 A Taxonomy of Covert Channels

In computer security, a *covert channel* is a type of attack that creates an unintended communication path to transfer information in a way that is unauthorized and violates a system's security policy. These channels are notoriously difficult to detect because they exploit legitimate, shared resources for purposes beyond their intended function. To understand the diverse nature of these threats, a formal classification is necessary.

The foundational work in classifying these channels was established by Butler Lampson in his seminal 1973 paper, "A Note on the Confinement Problem" [30]. While addressing the confinement problem—the challenge of preventing a program from leaking sensitive information—Lampson formally identified that even secure systems could be subverted through these unintended communication paths. His most enduring contribution was the fundamental distinction that divides covert channels into two primary categories–storage channels, which communicate by modifying a shared resource, and timing channels, which communicate by modulating the timing of events–discussed in detail below.

2.1 Covert Storage Channels

A covert storage channel [16, 65, 66] functions by modifying a shared resource or physical state—such as a file, a memory location,

Table 2: Forensic Relevance of SSD Memory Components

Memory Type	Relevant?	Justification
NAND Flash	✓	Primary non-volatile storage; data remnants may persist due to over-provisioning, wear leveling, and logical-physical mapping artifacts.
DRAM (DDR)	✓	Volatile cache; may contain mapping tables or buffered writes, recoverable shortly after power loss.
pSLC Cache	✓	High-speed NAND write buffer; may hold unflushed or hidden data following abrupt shutdowns.
SRAM	✗	Embedded in the SSD controller; inaccessible under typical forensic conditions.
SDRAM	✗	Legacy term; superseded by DDR variants in modern SSDs. Rarely encountered today.

or a packet header—which a receiving process can later observe. The communication is typically asynchronous, as the receiver does not need to be observing at the exact moment the sender modifies the state. For example, a sender could hide data in the file system by manipulating timestamps, in network traffic by embedding data in packet headers, or in more advanced channels by altering the physical properties of the storage medium itself. One SSD-relevant example involves manipulating the internal over-provisioning or wear-leveling behavior of the drive. An attacker with firmware-level access could deliberately trigger write amplification by repeatedly writing to specific logical block addresses (LBAs), which forces the SSD to allocate new physical blocks in a controlled pattern. A cooperating receiver, also with firmware access or system-level telemetry, could then infer the hidden data by analyzing the resulting changes in physical-to-logical mapping or wear-level counters. Because this method leverages internal controller state that is not exposed to the host OS or standard forensic tools, it operates as a stealthy, firmware-resident storage channel invisible to conventional analysis pipelines.

2.2 Covert Timing Channels

In contrast, a covert timing channel [2, 31, 69] encodes information by modulating the timing of system events or the performance of a shared resource. The receiver decodes the information by measuring these time-based variations. This method does not store data on the target medium, making it exceptionally difficult to detect with traditional storage forensics. These channels can be host-based, such as when a malicious process creates contention for disk I/O, or network-based, by modulating the time delays between sent packets. The most relevant examples for SSDs are hardware-based timing channels that exploit latency variations in internal operations such as garbage collection or wear leveling. For example, an attacker can modulate the frequency of TRIM commands or force the SSD into frequent block erasures to create detectable latency patterns. A cooperating receiver, measuring access times or I/O delays, can decode this signal without relying on any stored data—making the channel both transient and highly stealthy.

This foundational classification of channels–storage and timing–remains the standard starting point for analysis. To provide a more granular framework for modern threats, a main contribution of this paper is a novel, multi-dimensional taxonomy, which is detailed in Table 3.

3 Information Hiding Mechanisms in SSDs

The internal design of SSDs, while aimed at optimizing speed and longevity, unintentionally facilitates information hiding. Key controller operations—such as *wear leveling*, *garbage collection (with TRIM)*, and *over-provisioning*—disrupt straightforward mappings between logical and physical data locations, making it difficult to track, recover, or verify data state.

Notably, garbage collection is not instantaneous; deleted data may persist in invalid blocks for an indeterminate period. Additionally, over-provisioning reserves 7˜28% of the drive's capacity as controller-managed space, which remains inaccessible to standard forensic tools. These behaviors can be leveraged to conceal data fragments in areas inaccessible to conventional forensic tools, or to delay or obscure deletion timelines in ways that complicate forensic correlation and analysis.

SSDs incorporate several types of memory, each with distinct roles in storage, caching, and control. From a forensic perspective, however, not all are equally relevant to information recovery or concealment. Table 2 summarizes their significance in these contexts.

3.1 Hiding in Transient and Inaccessible Storage Areas

The Attack Vector. Three core SSD functions—*wear leveling*, *garbage collection (with TRIM)*, and *over-provisioning*—collectively create a storage substrate that is transient, non-deterministic, and partially inaccessible to traditional forensic tools. Wear leveling continuously redistributes data across physical blocks to ensure even usage, leaving behind stale data in previously written locations. Garbage collection reclaims invalid blocks asynchronously, meaning that deleted data may persist physically for an indeterminate period. Over-provisioning reserves 7–28% of total flash capacity as controller-only scratch space, typically invisible to the host system and standard acquisition tools.

Information Hiding Opportunity. The resulting data remanence forms a latent storage layer composed of obsolete, unmapped, or logically deleted content. This volatile region can be exploited for covert storage or may inadvertently retain sensitive information well beyond its logical deletion—particularly in drives where garbage collection is deferred or wear leveling is aggressive.

Table 3: Taxonomy of Covert Channels

Dimension	Category	Description	Examples and Subtypes
Transmission Medium	Storage Channel	Encodes data by modifying shared storage state that is later read. No timing coordination required.	*Subtypes:* • **File System Based:** Exploits logical metadata by manipulating file names [54, 58], timestamps [13, 18, 36], and permissions [11] within specific file systems like **JFS** [15], **XFS** [64], and **NTFS** [21]. • **Inaccessible Space:** Uses hardware or firmware-level areas invisible to the OS, including over-provisioned space [59], hidden partitions [44, 47, 72], slack space [53, 55–57], and unallocated space [3]. • **Network-based:** Embeds data within network protocols by using packet headers (**TCP/IP** [32, 35, 49]), payloads (**HTTP** [9, 14], **DNS** [7, 12, 41], **ICMP** [46, 51, 60], **NTP** [1, 20, 50]), or custom handshake protocols [52]. • **Physical Modification:** Encodes data by intentionally altering cell wear to affect flash program timing [17]. • **Behavior-based (State):** Modifies a persistent state that is read by the receiver. – *Wear-Leveling Induction:* Provokes detectable block relocation patterns. – *Error-State Feedback:* Triggers changes in ECC counters or logs.
	Timing Channel	Encodes information in variations of timing—such as access latency or execution delays—caused by sender activity and measured by the receiver.	*Subtypes:* • **Resource Contention (Host):** Sender occupies a shared local resource (e.g., SSD I/O, memory bus); receiver measures slowdown. • **Network-based:** Modulating inter-packet gap [10, 33, 71], or packet ordering. • **Behavior-based (Timing/Events):** Modulates performance or events over time. – *Garbage Collection Triggers:* Induces throughput degradation. – *Event-Based Signaling:* Uses presence/absence of actions in time slots. – *Thermal/Energy Signaling:* Modulates power load to cause observable throttling.
Resource Type	Software-based	Exploits software constructs or shared logical resources.	Shared memory, file locks, named pipes
	Hardware-based	Uses physical components or microarchitectural state.	CPU cache, branch predictor, power usage, EM emissions
Synchronization	Synchronous	Sender and receiver are time-coordinated.	Polling shared resources at known intervals
	Asynchronous	No timing coordination needed between parties.	Reading hidden files or blocks at any time
Intent	Malicious	Used for stealthy data exfiltration or unauthorized comms.	Malware using header fields, firmware-level hiding
	Legitimate/ Research	Used in controlled experiments or for demonstration.	Academic proof-of-concepts of timing-based or file-based channels
Detectability	Noisy	Introduces system anomalies that may be detectable.	Increased latency, performance drops
	Noiseless (Stealthy)	Mimics normal behavior; hard to distinguish.	Modulating wear-leveling patterns, subtle packet timing
Embedding Domain	Network-based [70]	Embedded in network protocols or traffic.	IP header fields, DNS tunneling, covert HTTP traffic
	Host-based	Within a single system using local resources.	Cache side-channels, semaphores, memory pages
	Storage-based	Exploits storage device internals or filesystem features.	SSD overprovisioned space [59], NTFS ADS [21], FTL

Security Implications. From a data sanitization perspective, wear leveling, garbage collection, and over-provisioning undermine guarantees of complete erasure, increasing the risk of residual data leakage. These mechanisms can retain sensitive data fragments beyond user control, complicating secure deletion and data privacy assurances.

Forensic Implications. The same transient and inaccessible storage areas may serve as a reservoir for evidentiary artifacts in forensic investigations. However, recovery is often unreliable due to the unpredictable and opaque behavior of the SSD's internal controller processes, which dynamically relocate and erase data.

3.2 Firmware-Level Hiding Techniques

The Attack Vector. The SSD controller runs complex proprietary firmware, including the critical FTL, which maps LBAs to physical flash pages. This firmware constitutes a major attack surface. Compromised firmware can manipulate FTL mappings to establish covert storage areas.

Information Hiding Opportunity. Firmware-based concealment methods include:

- *Hidden Mapping:* Firmware reserves physical flash blocks unmapped to any LBA, rendering them invisible to the OS but accessible for covert data storage.
- *Dynamic Remapping:* The FTL may falsely mark good blocks as "bad" to the OS, retiring them from normal use and reallocating them for hidden storage.
- *Firmware Rootkits:* Malicious code embedded within firmware creates persistent, stealthy footholds that survive formatting and OS reinstallations.

Security Implications. Firmware-level implants represent a critical threat to data security due to their persistence beyond disk formatting and operating system (OS) reinstallation. These implants operate stealthily within proprietary firmware, evading conventional detection methods and enabling long-term unauthorized access or manipulation of data.

Forensic Implications. Forensic analysis of firmware implants is exceptionally challenging because of the closed-source and proprietary nature of SSD firmware. Detecting and mitigating such compromises requires advanced reverse engineering skills and deep knowledge of SSD internals, placing these investigations beyond the reach of standard forensic tools and typical analyst expertise. Moreover, reverse engineering must be performed separately for each specific firmware version and vendor, as implementations vary widely and are typically undocumented.

3.3 Physical-Layer Hiding Techniques

The Vector. This technique bypasses logical data structures entirely, operating at the analog level of the flash memory cells. By manipulating physical properties such as program time, a compromised controller can encode data invisibly within the hardware layer. These modifications are easily concealed under the guise of normal background operations like garbage collection and wear leveling, making them difficult to detect.

Information Hiding Opportunity. Data is encoded by physically altering the analog properties of ReRAM cells through controlled pre-conditioning or managed wear. For instance, one technique involves manipulating the initial 'Forming' condition of the cells to change the number of pulses required for a subsequent SET operation [43]. Another method involves intentionally 'stressing' cells with repeated write cycles to controllably increase their set/reset time [17]. Heavily stressed cells program faster (representing a binary '1'), while less-stressed cells program slower (binary '0'). Since these changes mimic natural aging patterns of SSDs, they remain undetectable through standard logical or file-system-level analysis. In both cases, because the modifications are independent of logical data, the hidden information is exceptionally persistent, surviving secure erase procedures, formatting, file deletion and defying standard forensic analysis.

Security Implications. This method creates a highly persistent and stealthy covert channel. It leverages fundamental physical behaviors of the hardware to encode data without modifying user-visible content or meta-data, evading all traditional detection methods. The ability to survive sanitization protocols poses a severe risk in environments requiring strong data confidentiality guarantees.

Forensic Implications. Forensics investigators face substantial barriers in detecting and analyzing such hiding methods. Detection requires invasive chip-off procedures and advanced instrumentation capable of measuring per-cell program timing. Even with full physical access, distinguishing malicious wear patterns from natural usage-induced variance is extremely challenging, rendering this one of the most forensically resilient forms of information hiding.

4 SSDs as Active Attack Vectors

Beyond their passive role in data storage, modern SSDs' complex, reprogrammable firmware makes them potent vectors for active attacks on host systems. Drawing parallels to the well-known BadUSB vulnerabilities [40], an SSD can transcend its storage function and become a weaponized peripheral capable of injecting malicious commands and establishing persistent backdoors.

4.1 From BadUSB to BadSSD: Firmware as a Security Blind Spot

The BadUSB attack, demonstrated by Karsten Nohl and Jakob Lell at Black Hat USA 2014 [40], exposed the hidden risks of USB device firmware. Their research showed that USB peripherals—such as flash drives—can be reprogrammed at the controller level to impersonate other devices (e.g., keyboards, network adapters), enabling arbitrary code execution, stealthy data exfiltration, or user surveillance. These attacks bypass traditional antivirus defenses entirely, as the payload resides in the device firmware rather than in the file system.

This paradigm of firmware-level compromise extends to SSDs, whose embedded controllers manage critical operations like wear leveling and garbage collection—processes opaque to the host OS and forensic tools. If subverted, SSD firmware can embed covert channels, hide data persistently, or sanitize content automatically without user knowledge.

Table 4: Mitigation Strategies for Firmware-Level Attacks

Method	Description
Device Whitelisting	Restricts system access to approved devices based on vendor or product identifiers. Implemented through endpoint protection platforms or host-based access control policies.
Firmware Signing	Ensures only authenticated firmware images are executed by the device. Relies on cryptographic signatures verified by the host or controller prior to installation.
Hardware Monitoring	Uses hardware-based telemetry or firmware integrity tools to detect deviations in device behavior, access patterns, or performance characteristics.
Port Management	Disables unused or untrusted I/O interfaces (e.g., USB, SATA) via BIOS/UEFI settings or firmware configurations to reduce attack surface.
User Awareness	Educates users to avoid untrusted peripheral devices, recognize suspicious hardware behavior, and report anomalies to IT or security teams.

Thus, the BadUSB attack model serves as a conceptual precedent for SSD-resident threats. Despite the similarity, SSD firmware security remains underexplored. Recent work [8] shows promising directions by using side-channel power analysis to detect firmware modifications with high confidence, highlighting potential for improved SSD firmware validation.

4.2 Firmware-Level Exploitation

Firmware-level exploitation targets the low-level controller code embedded within SSDs. Unlike user-space or even kernel-level malware, firmware implants operate entirely outside the visibility of the host OS. Malicious firmware can be installed by exploiting vendor update mechanisms or undocumented firmware flashing utilities. Once installed, it can persist across disk formatting, OS reinstallation, and even standard forensic imaging, making it a particularly effective tool for long-term persistence and anti-forensics.

Key characteristics of firmware-level exploitation include:

- **Firmware Malware Persistence:** Malicious code embedded in the SSD controller's firmware resides outside of the logical storage medium, making it invisible to OS-level tools and traditional antivirus software. This allows malware to survive even low-level disk wipes.
- **Device Behavior Manipulation:** Modified firmware can implement covert channels, dynamically hide or reveal data, or initiate autonomous data destruction routines. For instance, an attacker may program the firmware to ignore deletion requests, delay writes, obfuscate specific LBA ranges from security and forensic tools, or transparently redirect reads to serve trojanized versions of system files or commands under certain conditions.
- **Trust Assumptions:** Most systems implicitly trust device firmware and lack native mechanisms to validate or authenticate the integrity of embedded controller code at boot. As a result, a compromised firmware can subvert trust models built into the OS or security software creating a critical blind spot in the chain of trust, where malicious firmware can execute prior to any authenticated software stack. Trusted Computing approaches, such as TPM-based secure boot, often do not extend their integrity checks to peripheral or storage firmware.

Firmware-level threats are particularly dangerous in forensic and security-sensitive contexts because of their stealth and resilience. For example, Kaspersky Lab's analysis of the *Equation Group (APT-C-40)* revealed firmware implants in hard drives from major vendors demonstrating real-world viability of this vector. Specifically, the malware used in their operations, dubbed *EquationDrug* and *GrayFish*, was found to be capable of reprogramming hard disk drive firmware along with being able to create and use hidden disk areas and virtual disk systems for its purposes [42, 68]. While SSDs have different architectures, their complexity and closed firmware ecosystems make them equally vulnerable if not more. Without vendor support or hardware-level tools, detecting such modifications is exceedingly difficult.

4.3 Mitigation

Effective mitigation of firmware-level attacks requires hardware-centric controls, firmware integrity verification, and organizational security policies. As summarized in Table 4, these approaches include cryptographic firmware signing, device whitelisting, and continuous hardware monitoring. Despite these efforts, detecting malicious firmware remains extremely challenging. Without vendor support or hardware-level tools, identifying such modifications is exceedingly difficult. Effective detection typically requires hardware-assisted analysis or vendor-assisted verification of firmware integrity.

5 Future Outlook and Emerging Challenges

As solid-state storage technologies mature and diversify, new architectural, interface, and usage paradigms are reshaping the security and forensic landscape. While traditional concerns such as data remanence and firmware manipulation remain relevant, the next generation of SSDs introduces unique challenges—and in some cases, new opportunities. This section explores the evolving ecosystem of SSD technologies, starting with the rapidly adopted NVMe interface, and outlines emerging concerns that forensic analysts and security professionals must address moving forward.

5.1 The NVMe Interface: New Security and Forensic Hurdles

As SSD technologies continue to advance, the adoption of the NVMe (Non-Volatile Memory Express) interface introduces new dimensions to the forensic and security analysis of SSDs. Designed for high-throughput and low-latency communication over the PCIe bus, NVMe departs significantly from traditional SATA-based protocols like AHCI. While NVMe offers substantial performance benefits, it also introduces challenges that can hinder forensic access and data recovery:

- **Opaque Firmware Behavior:** NVMe controllers often implement proprietary wear leveling, over-provisioning, and error correction strategies that are less transparent than those in SATA SSDs.
- **Rapid and Secure Deletion:** Features such as fast TRIM and secure erase are more efficiently implemented, potentially eliminating forensic traces more thoroughly and quickly.
- **Namespace Abstraction:** NVMe supports multiple namespaces—logical divisions of storage—which may enable data compartmentalization or covert channels that complicate forensic discovery.
- **Limited Tool Support:** Many traditional forensic tools are optimized for SATA-based SSDs and lack deep support for NVMe-specific structures or commands.
- **Advanced Power Management:** Aggressive power-saving states and write caching behavior can affect data persistence after shutdown, reducing opportunities for cold-boot or residual data recovery.

As NVMe becomes the default interface in both consumer and enterprise storage, forensic practitioners must adapt their methodologies and tools to address these emerging obstacles. The shift highlights the broader trend: SSDs are no longer passive storage devices but increasingly intelligent systems that actively shape data accessibility and visibility—often beyond the analyst's control.

5.2 Beyond NAND: Emerging Memory and Future Challenges

The security and forensic landscape of solid-state storage is not static; it evolves with the underlying hardware. While this paper focuses on the security opportunities and forensics challenges presented by NAND flash-based SSDs, it's critical to consider the emerging technologies that will shape the future of non-volatile memory. As next-generation memories like Resistive Random-Access Memory (ReRAM), MRAM (Magnetoresistive RAM), and PCM (Phase-Change Memory) mature, they each introduce a new set of security paradigms. Because the underlying physics is completely different for each technology, the methods an attacker would use to exploit that physics—the physical-layer attack surface—must also fundamentally change. Security challenges of these evolving memories are presented in [27, 28, 61–63]. Below we discuss the security implications and forensics challenges of these three emerging technologies.

5.2.1 ReRAM (Resistive RAM). Resistive RAM (ReRAM) is an emerging type of non-volatile memory that stores data by switching a dielectric material between different resistance states. Typically, a low-resistance state (LRS) represents one binary value, and a high-resistance state (HRS) represents the other. This resistive switching is achieved by applying electrical voltage across the material, often implemented using memristive elements.

Security Implications The shift from NAND flash to ReRAM fundamentally alters the *physical-layer* attack surface. Covert storage channels based on manipulating the program time of flash cells would become obsolete. They would likely be replaced by new techniques exploiting analog and physical properties [17, 43].

Forensic Implications This creates new forensic challenges, as the tools and methodologies developed for analyzing data remanence and wear patterns in NAND flash will not apply to ReRAM's different architecture. A new generation of forensic techniques will be required to recover data and detect tampering on these future devices. Information hiding techniques exploiting ReRAM

5.2.2 MRAM (Magnetoresistive RAM). As another leading contender in emerging memory, MRAM stores data using magnetic states rather than electrical charges. Each cell contains a magnetic tunnel junction that has a low or high electrical resistance depending on the orientation of its two magnetic layers.

Security Implications This technology is immune to the charge-based physical-layer attacks seen in NAND flash. However, new covert channels could emerge, potentially by manipulating magnetic spin-torque transfer or by detecting subtle, unintended magnetic field variations between cells. MRAM's near-infinite endurance also renders any wear-based hiding techniques obsolete.

Forensic Implications Forensic analysis would shift entirely to the magnetic domain. Recovering data remnants would require new tools capable of reading faint magnetic states, such as magnetic force microscopy, rather than detecting trapped charges.

5.2.3 PCM (Phase-Change Memory). PCM is a non-volatile memory technology that works by changing the physical state of a chalcogenide glass material. By applying heat with an electrical pulse, the material is either melted and rapidly cooled into a high-resistance amorphous state (a '0') or heated to a lower temperature to settle into a low-resistance crystalline state (a '1'). Intel's Optane products were the most prominent commercial example of this technology.

Security Implications The physical attack surface shifts to the material's phase. A potential covert channel could involve creating and detecting partially-crystallized, intermediate states that are not used for normal data storage. The heating process itself could also be exploited to create thermal side-channels.

Forensic Implications. Forensic investigators would need methods to analyze the physical phase of the storage medium. Data remanence would depend on how perfectly the material can be reset (amorphized), as incomplete phase transitions could leave behind recoverable traces of the previous crystalline structure.

6 Conclusion

This review has shown that SSDs both strengthen data security and introduce complex new attack surfaces. Architectural features like garbage collection (with TRIM), wear leveling, and the FTL offer inherent data sanitization and resistance to physical forensics—yet also enable covert storage, traceless timing channels, and firmware-based attacks such as device spoofing and DMA via NVMe.

As storage shifts toward post-flash technologies (ReRAM, PCM, MRAM) and higher-bandwidth protocols, legacy forensic tools lose relevance. New methods will be required to detect tampering, recover hidden data, and evaluate trust. Whether SSDs are a friend or a foe depends not on their design alone, but on how their capabilities are understood, secured, and audited.

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A Security Implications of SSD

Table 5: Summary of Inherent SSD Security Characteristics

Category	Mechanism / Feature	Description	Security Implications	Example(s)
1. Inherent Data Sanitization & Anti-Forensics	TRIM & Garbage Collection (GC)	SSDs use the TRIM command to mark deleted blocks as invalid, which are later wiped during idle garbage collection cycles.	Makes recovering deleted files significantly more difficult, especially for casual or opportunistic attackers.	A soldier deletes recon files from a field laptop; due to TRIM and GC, data is virtually unrecoverable if the laptop is lost or seized.
			Even advanced forensic tools struggle to reconstruct deleted data on SSDs.	In post-capture analysis, adversaries fail to recover wiped mission data due to natural obfuscation caused by TRIM and wear-leveling.
	Wear-Leveling & Data Fragmentation	Wear-leveling spreads writes across many memory cells to prolong lifespan, causing fragmented and scattered file storage.	Complicates forensic reconstruction, making overwritten data on SSDs much harder to recover than on HDDs.	Surveillance footage on an SSD-equipped drone ground station leaves minimal forensic traces even after deletion.
			Wear-leveling makes file carving and forensic recovery far more difficult—even for specialized forensic tools.	After a drone crash, adversaries attempting file carving from recovered SSDs find no reconstructible image or mission logs.
	Unpredictable Physical Layout	SSDs use flash translation layers and wear-leveling algorithms, so data is not written linearly or tied to physical sectors.	Even without encryption, SSDs are more resistant to physical forensics than HDDs due to layout obfuscation.	A confiscated SSD from a field team provides little to no usable intelligence due to its unpredictable mapping—even without encryption.
2. Always-On Encryption & Instant Sanitization	Self-Encrypting Drives (SEDs)	Many modern SSDs include hardware-level encryption (e.g., AES-256) that encrypts all data at rest, always active by default, with no user configuration needed and no performance penalty.	Encryption is seamless, less error-prone, and harder to tamper with than software-only solutions encouraging wider adoption.	A mobile command laptop encrypts data automatically, avoiding human setup errors and ensuring encryption is always enforced under stress.
	Cryptographic Erase (Crypto-Erase)	Since data is encrypted, secure deletion can be performed instantly by erasing the encryption key.	SSDs support ATA Secure Erase and NVMe Format NVM commands that wipe even over-provisioned areas instantly.	Before retreating from a temporary command post, an officer triggers a crypto-erase on the SSD, making the entire drive unreadable in seconds.
				A forensic analyst decommissions hundreds of SSDs for secure disposal using crypto-erase, with zero remnant data risk.
3. Physical and Operational Security	No Magnetic Residue	SSDs are immune to magnetic remanence attacks, as they do not store data magnetically.	Removes an entire attack vector used to recover deleted data from HDDs.	An SSD recovered by adversaries cannot be analyzed with magnetic forensics tools that work on legacy drives.
	Durable by Design	No moving parts means SSDs are resilient to shocks, drops, and vibration.	Durability preserves data integrity and availability after physical events.	SSD-equipped gear in airborne or mobile operations survives rough handling without loss of mission data.

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Table 5 – continued from previous page

Category	Mechanism / Feature	Description	Security Implications	Example(s)
	Self-Destruct Mechanisms (select models)	Specialized SSDs may include hardware-triggered self-destruction physically or logically destroying NAND components.	Enables extreme data protection for classified or high-risk environments.	A covert operative uses a laptop with a self-destruct SSD trigger destroying components upon tampering detection.
	Power Loss Protection (PLP)	Onboard capacitors and firmware maintain filesystem consistency during power loss by flushing data safely to NAND.	Mitigates power-cycling (write hole) attacks by preventing torn writes and metadata corruption, protects against DoS and environmental corruption.	A targeting computer in a tactical vehicle preserves critical software integrity despite unstable power feeds during maneuvers.
			Prevents data rollback attacks ensuring critical updates persist, avoiding system reversion to outdated, vulnerable states.	A UAV ground station's urgent map update is securely committed; PLP stops a power glitch from reverting the UAV to a dangerous flight plan.
			Enhances forensic data reliability by preserving unbroken audit trails and logs.	A tactical drone's "black box" saves final telemetry and video during a hard landing power loss for post-mission analysis.
4. Side-Channel Resistance	No Acoustic or Electromechanical Leakage	SSDs lack moving parts, actuator arms, or spinning platters, emitting no mechanical or acoustic signatures.	Inherently more resistant to side-channel attacks like acoustic or electromagnetic eavesdropping.	In a secure mobile command vehicle, SSDs eliminate acoustic cues that might leak activity patterns to passive sensors.
	Lower Firmware Malware Persistence	Firmware in SSDs is often more tightly controlled and locked down than in HDDs.	SSDs typically present a narrower attack surface for persistent, low-level malware, though not immune.	Adversaries targeting firmware persistence find fewer attack paths on SSDs than legacy spinning disks in ruggedized laptops.
5. Performance-Driven Security Enablement	Instant Boot for Rapid Response	SSDs enable near-instant boot and faster app launches, critical during security incidents.	Speed improves proactive threat mitigation and reactive containment during cyberattacks.	A red team simulation triggers a lockdown; SSD-equipped systems reboot and isolate endpoints in seconds, preventing full compromise.
	Faster Full-Disk Encryption (FDE)	High throughput makes SSDs more efficient for full-disk encryption tools (e.g., BitLocker).	Users are more likely to adopt strong encryption when performance costs are negligible.	A cyber defense team in a NATO base uses FDE across endpoints; SSD speed ensures no trade-off in operational tempo.
	Rapid Scanning & Threat Response	Antivirus, anti-malware, and EDR tools scan faster on SSDs, improving real-time threat detection.	Enhances proactive and reactive security workflows without compromising usability.	An edge cyber sensor unit uses SSDs for faster reboots and full scans between missions in low-dwell zones.