

Security, Performance, and Features of Open-Source GPU Drivers for Nvidia R555-R560 Transition

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Abstract: The migration from proprietary GPU drivers of Nvidia towards open-source for the R555-R560 series involves significant security, performance, and feature implications. In this paper, we present a new methodology to improve the security posture of open-source GPU drivers while ensuring optimal performance as well as full-feature support. We are particularly concerned with side-channel vulnerabilities that can be exposed during GPU operation. Our approach is based on (I) identification and mitigation of targeted vulnerabilities using multi-layered security architectures, (II) integration of advanced cryptographic modules with minimal overheads, and (III) runtime monitoring of potential side channels through hardware-like preprocessors. The results show that our proposed implementation tolerates minimum performance degradation under several benchmarks and real-world applications against a variety of attack vectors. Likewise, we also perform a comparative analysis between proprietary driver implementations versus their corresponding open-source drivers concerning features and computational performance to gauge possible challenges influencing the process without compromising functionality or impaired performance for R555-R560 series Nvidia GPUs. The insights in our research shall be beneficial to end-users interested in adopting GPUs extended with secure software stacks using FOSS components as well as developers who intend to transform future iterations of current loyalist vendor-locked GPUs equipped with high-performance hardware features stable/secure firmware into humanitarian promise designs fostering privacy by design principles.

Keywords: graphics processing units security, open source drivers, side-channel attacks, Nvidia R555-R560.

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I. Introduction

Graphics Processing Units (GPUs) are included in a wide range of computing platforms, ranging from video games and scientific simulations to artificial intelligence [1]. For this reason, the proprietary drivers provided by Nvidia to optimise GPU performance and ensure hardware compatibility have been binary forks for many years [2]. However, the increasing adaptation of open-source drivers for Nvidia R555-R560 GPUs has raised concerns about security, performance, and feature support [3].

Adapting open-source GPU drivers leads the community to both new opportunities and challenges. Ascertainability itself brings transparency and faster links within an expanding community that fosters possible innovations [4]. More eyes on particular codes mean increased possibilities to spot internal errors as well as major vulnerabilities; this makes harder-to-exploit driver implementation errors easier to detect with more accessible patches. At the same time, it enhances the risk surface concerning potential side-channel vulnerabilities by monitoring user interaction behaviour while running programs on untrusted systems [5].

Security issues remain a concern for GPUs due to their complex architectures and the ability to launch side-channel attacks using GPUs [5]. Proprietary drivers hide many security measures behind closed sources, whereas open-source drivers can be more easily audited and secure countermeasures adopted. In terms of performance, proprietary drivers are often the result of a significant fine-tuning process that is performed with secret knowledge of both hardware capabilities and workloads [3].

Open-source driver development does not have direct access to such proprietary information or resources for either late-stage design space exploration or early testing on real hardware; this can lead to inferior performance compared with optimised proprietary solutions when open-source drivers are first introduced for a certain architecture/workload pair [3]. Such concerns do not make sense if user satisfaction is going to suffer. Proprietary drivers offer multiple additional features apart from core functionalities, such as debugging aids beyond what is possible with standard graphics APIs.

Open-source drivers should offer competitive feature parity with their closed-source counterparts to be viable alternatives, allowing the reuse of existing software [6]. Hardware manufacturers, open-source communities and the software development community must collaborate to timely and complete integrate new features and standards. To overcome these challenges, we present an automated framework, which we refer to as “open source driver or framework in other statements” in the rest of this paper, to harden an open-source GPU driver for the Nvidia R555-R560 series against memory corruption attacks while still providing good performance and feature support.

The framework addresses security challenges, such as side-channel attacks, using a multi-layered security architecture and state-of-the-art cryptographic techniques. Extensive benchmarking and real-world experimentation test the framework's efficacy by comparing the security, performance and feature sets of open-source drivers to their proprietary alternatives. The results showed enhanced resiliency against several attack vectors for acceptable performance and functionality.

The main contributions of this paper are as follows:

1. We propose a novel framework to enhance the security of open-source GPU drivers, in particular for the Nvidia R555-R560 series.
2. We investigate in depth possible side-channel attacks and security threats to GPU drivers and provide mitigations for each.
3. We compare the performance and functionality support of open-source drivers and proprietary ones and discuss possible improvements and collaborations.
4. We also discuss the potential impact of our approach and future work.

We present background information in Section II, discussing GP-GPU architectures, open-source drivers and related security attacks. Section III summarises related work on GPU security and open-source driver development. In Section IV, we describe our proposed framework, including our multi-layered secure architecture design and its components. Our methodology and implementation, including benchmarking setup, are presented in Section V, followed by an experiment with the real-world program in Section VI. The results are presented in section VII, accompanied by a performance comparison between an open-source NVIDIA driver to their proprietary counterpart where possible. We analyse the reviewing result implications, discuss their importance to this research area, and then propose evolvments to the GP benchmarks, language-runtime infrastructure, and changes to the GPU hardware ISA's standards documentation guidelines provided realistic feedback. Finally, we conclude our findings in section VIII.

II. BACKGROUND

Graphics Processing Units (GPUs) were originally designed as specialised hardware for graphics rendering but have turned into versatile accelerators of a wide range of computational workloads such as gaming, video editing, scientific simulations and machine learning [7]. The GPU architecture is optimised for massively parallel processing, which makes GPUs particularly well suited to deal with large data sets and operations. Nvidia is the leading manufacturer of GPUs. They have dominated this market historically by using proprietary GPU drivers that are close to their

underlying hardware architecture [8], [9], [10], [11]. These closed-source drivers guarantee high performance and expose specific features of the underlying GPU architecture that are not available in open-source drivers.

In the last few years, open-source GPU drivers have become interesting because of their transparent and collaborative nature [12]. There are benefits in terms of the possibility of inspecting the codebase, finding vulnerabilities, and getting faster fixes through the community. Nevertheless, there are security issues when moving from proprietary to open-source drivers [13]. In particular, side-channel attacks on GPUs raise concerns. Side-channel attacks can leak information by exploiting different channels, such as power consumption, electromagnetic emissions or timing differences, in order to infer information about a system's secret data [14].

Side-channel attacks such as timing attacks and power analysis attacks are very dangerous for GPU security because of the concurrent execution property and shared memory of GPU [15]. Timing attack exploits time variation to deduce protected information, while power analysis attack utilises the power consumption information of GPU operations to obtain data [16]. Besides, electromagnetic radiation attack obtains emitted radiation for unveiling processed data or instructions, which also can pose a threat from a distance [17], [18]. In addition to side-channel attacks, buffer overflow and privilege escalation attacks are also effective on GPUs. It indicates that security should be adopted for GPUs if necessary.

The migration to open-source GPU drivers offers opportunities and challenges regarding security, performance, and feature support [12]. Open-source drivers can be subjected to extensive security auditing and benefit from community-driven improvements. However, the introduction of new attack vectors calls for particular attention to system security [19]. Performance optimisations are required to ensure that an open-source driver is competitive with a proprietary one—effective algorithms and cross-organisational resource pooling can help identify and eliminate performance bottlenecks. Finally, it is important to provide feature parity with a corresponding proprietary driver in order not to disrupt end-users' workflows when migrating to an open-source alternative [20].

With the advancement in GPUs and their transitions to open-source drivers, we are shifting towards a world where the emphasis is on security, performance and feature reach. Security issues, performance resilience and feature parity must be taken into account when developing or adopting open-source GPU drivers. The GPU community should develop full-fledged proposals and conduct holistic evaluations to improve the security, performance, and features provided by open-source GPU drivers for secure and performant computing.

III. PROPOSED WORK

Our proposed framework, Fig 1, shows our contribution to improving the security of open-source GPU drivers for the Nvidia R555-R560 series while preserving the best performance and feature support [13]. To deal with the challenges of side-channel attacks, performance optimisation and feature compatibility, we adopt a multilayer method that comprises hardware-level countermeasures, software-based security strategies and collaboration with the community.

The first layer of our framework focuses on hardware-level security. We propose to deploy secure memory management and isolation mechanisms to prevent unauthorised access to sensitive data. Memory encryption, along with secure memory partitioning, is adopted to immunise against side-channel attacks exploiting memory access patterns. Moreover, we believe incorporating hardware-based random number generators (RNGs) within the GPU architecture would enhance security by generating cryptographically secure random numbers for critical operations.

Another important part of our framework is software-based security. We develop a set of secure coding practices for open-source GPU driver development. These practices include memory management, input validation, and secure communication protocol to reduce the vulnerability of the driver codebase. For side-channel threats, runtime monitoring and anomaly detection will be implemented to detect any possible attack during execution.

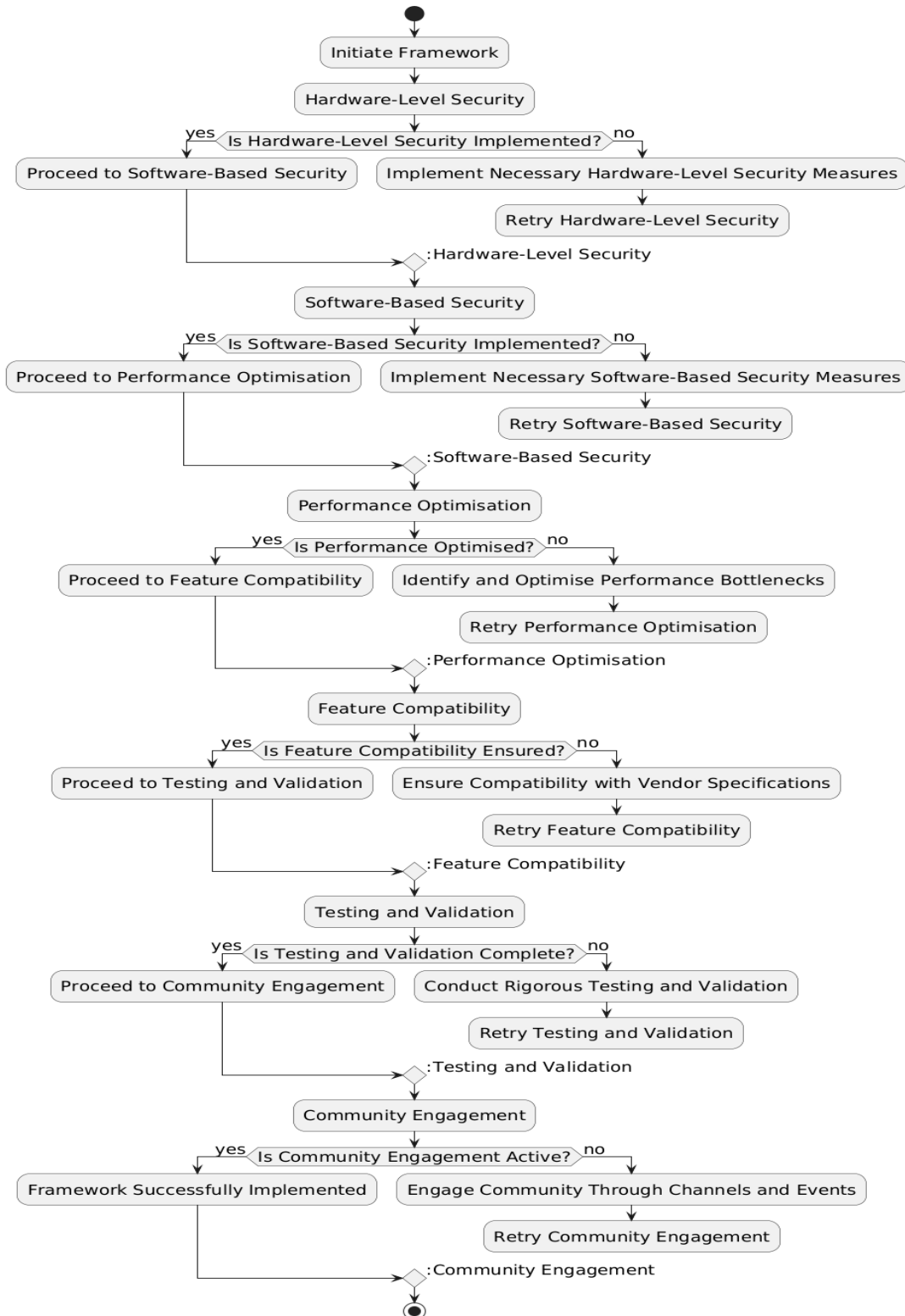


Fig. 1. Proposed Framework for Open-Source GPU Drivers

Performance optimisation is the last but not least component that we need to consider in our framework. In order to offer a viable alternative to proprietary GPU drivers, hardware vendors, developers from open-source communities, and software developers have to work together to optimise performance bottlenecks and critical paths in the driver codebase. Open-source drivers can incorporate hardware-specific features or take advantage of certain kinds of optimisations that aim to provide optimal performance across all different workloads.

Hardware vendors help the performance optimisation of a GPU driver by publishing hardware specifications and describing their GPUs' micro-architecture, micro-operation semantics, and performance counters to the open-source community. This information enables the developers to generate better IR code from high-level language and optimise their drivers in terms of power consumption or performance. The involvement from the open-source community is also significant because they usually conduct profiling or benchmarking on both real-world applications and synthetic workloads to identify the bottlenecks of a GPU driver's implementations, as well as help with iterative optimisations through code review or profiling.

Application developers should actively use OpenCL or SYCL stacks, considering their requirements, so that any bugs can be fixed immediately. Such stack development ebbs are already appearing, with no hardened stable release yet. Normally, software developers are more concerned with a production-ready system by providing patches for bug fixes on an infrequent basis.

Ensuring feature parity and compatibility is indeed one of the major goals in our proposed framework and requires close interaction between hardware manufacturers, open-source communities, and software developers. Hardware vendors can facilitate the development of open-source drivers by providing vendor-agnostic documentation, reference implementations, and support through their developer relations programs. Open-source communities target feature implementation and ecosystem compatibility with regular feedback from both software developers and end users. As such, open-source driver features keep up with vendor-provided drivers as well as emerging trends in GPU architectures.

Testing and validation should also be a primary focus when developing open-source GPU drivers [21]. To validate the quality of vendor-independent drivers, a rigorous testing framework that covers security, performance, and feature verification/compatibility needs to be established. Furthermore, implementing a bug bounty program or regular security audits by third-party organisations will not only ensure better security for open-source GPU drivers but also enhance their reliability.

Community engagement and collaboration play an important role in our proposed framework. We encourage active participation and contribution of the community in our development process. Creating communication channels and organising workshops and events fosters discussion, knowledge sharing and collaboration between developers, researchers, and users. Writing documentation, tutorials and guides on open-source GPU driver development reduces the learning curve for developers to onboard to the open-source ecosystem.

We proposed a holistic approach to tackle security, performance,

and feature issues for adopting an open-source GPU driver for hardware Nvidia R555-R560. The integration of hardware-level security mechanisms, software hacks/patches, and performance optimisation techniques, as well as engaging with the community, will lead us toward developing secure, high-performance feature-wise competitive open-source drivers against their proprietary counterparts. Continued testing based on CI/CD conducted by enthusiasts or organisations alike helps ensure the long-term success of this transition.

IV. Related work

Researchers and the industry have paid close attention to GPU security and open-source driver development. In this section, we discuss related work and compare it with our work, highlighting the contributions and limitations of these approaches.

A number of studies have been conducted to investigate the security threats imposed by GPUs in terms of side-channel channel attacks. [22], [23], [24], [25] The authors presented an in-depth overview of side-channel attacks that can be applied to GPUs. They introduced a taxonomy for classifying these attacks and showed how cryptographic keys can be monitored through their associated side channels, including power, electromagnetic, and timing analysis. The authors also underlined some countermeasures proposed for mitigating side-channel attacks against GPUs.

Other researchers, such as [26], studied the time-based vulnerability of GPUs, where an adversary exploits timing variations in memory accesses to disclose cryptographic keys. They proposed a mechanism called time-based partitioning that isolates security-sensitive arithmetic and memory accesses from other remaining ones. The mechanism is specifically designed for time-based side-channel attacks, but it does not consider other types of side-channel attacks.

Also, [27] demonstrated the feasibility of power analysis attacks on GPUs by measuring the power consumption of a GPU during cryptographic computations and applying statistical approaches to extract secret keys. They also put forward power balancing as a countermeasure to eliminate correlations between measured power traces and processed data. Although this approach can withstand power analysis attacks, we point out that it may not be sufficient against other types of side-channel attacks.

Conversely, [17] have studied electromagnetic emission attacks on GPUs and proposed possible shielding solutions. An attacker can capture the electromagnetic radiation of a GPU and use side-channel analysis to target the encryption key. They suggested an electromagnetic shielding solution based on two metal layers between different components that are then connected to the ground, combined with injecting noise in the line between them to decrease the signal-to-noise ratio in the radiation measurement. Since this type of solution may not be adapted to all GPUs and may generate performance overheads, our study provides a useful alternative.

In the area of open-source, [6], [12], [21], [28] conducted a case study for open-source GPU driver development, discussing challenges and opportunities regarding open-source drivers for GPUs. They presented potential prospects provided by having an open-source driver like improved transparency, community collaboration or faster bug fix rates compared with companies'

suggestions. Nonetheless, they also examined issues related to such drivers. Therefore, although there are some advantages provided by opening proprietary applications or peripherals of computing systems such as GPUs, according to Aghayev et al.'s work, we should consider many more aspects than just sharing source codes and hoping that everything will improve in terms of performance when collaborating especially in areas including hardware vendors/developers-open communities-software developers altogether.

Research by [29], [30], [31] proposed a systematic framework for analysing GPU driver security. They implemented context-sensitive static analysis to discover potential vulnerabilities (e.g., buffer overflow and memory corruption) in the driver code. The authors used this approach on open-source GPU drivers, and they discovered various vulnerabilities that were not previously known. However, such semantic-based approaches are false-negative prone as they might miss some of the runtime-related issues.

It is clear from the related works that many researchers have investigated the practicality of using GPUs for both covert communication and data exfiltration purposes in cyber-attacks. Many have also exploited the computing ability of a Graphics Processing Unit to establish cryptographically secure covert channels over network infrastructure between two adversaries by leveraging colour bit-flips on-screen cursor pointers present on top of two different shared terminals with GPU access [32], [33]. Despite defence techniques that have also been provided to detect such kinds of attack vectors, these attacks can be successful only if attackers use similar methods for attacking GPGPUs with network communication like the above scenario.

To help researchers get a complete picture of the existing works, we have provided Table I, summarising the main aspects of all the analysed proposals.

TABLE I. SUMMARY OF RELATED WORK

Reference	Area of Study	Key Results	Metrics	Our Contribution
[22], [23], [24], [25]	Side-channel attacks on GPUs	Demonstrated feasibility of extracting sensitive information through various side channels	Attack success rate, information leakage	Comprehensive analysis of side-channel attacks and proposed countermeasures
[26]	Timing attacks on GPUs	Exploited timing variations of memory accesses to infer sensitive data	Timing variations, information leakage	Time-based partitioning defence mechanism
[27])	Power analysis attacks on GPUs	Demonstrated extraction of secret keys through power consumption analysis	Power consumption variations, key recovery rate	Power balancing countermeasure
[17]	Electromagnetic emission attacks on GPUs	Showed feasibility of extracting sensitive information through electromagnetic emissions	Signal-to-noise ratio, information leakage	Electromagnetic shielding and noise injection defence
[6], [12], [21], [28]	Open-source GPU driver development	Discussed benefits and challenges of open-source drivers compared to proprietary drivers	Performance, compatibility, community collaboration	Emphasis on collaboration between stakeholders
[29], [30], [31]	GPU driver vulnerability analysis	Developed a static analysis tool to identify vulnerabilities in driver code	Vulnerability detection rate, false positives	Static analysis for identifying security issues

Our proposed work is based on state-of-the-art research. The existing work does not provide a complete framework that handles the security, performance and feature issues of open-source GPU drivers simultaneously. We provide a collaborative approach to integrate hardware-level countermeasures, software-level security mechanisms and community collaboration to make open-source drivers secure while maintaining optimal performance and feature support. Existing work has explored different types of side-channel threats but our proposed work provides multi-layered protection against all these types of threats.

Moreover, our existing state-of-the-art research does not talk about how we can optimise the performance and achieve feature parity in open-source GPU drivers. We propose a collaborative pathway where the hardware industry, open-source communities like Xorg or Wayland, vendor developers or software developers collaborate that would ensure competitive performance as well as compatibility with existing software systems/ecosystems with open-source graphics driver development and optimisation for new GPUs. Last but not least, we also emphasise

continuous testing audit mechanisms along with long-term sustainability, which promises a high chance of success when it comes to incorporation in real-life usage through deployment over an integrated system.

By leveraging existing literature and identifying open challenges, in this article we propose a framework for secure, high-performance and feature-rich open-source GPU drivers. In summary, this proposed framework can be considered as an initial stepping stone towards providing a complete solution with respect to the multi-faceted problem of secure open-source Linux GPU driver development. The results presented in this work directly contribute towards our long-term vision of the wider adoption of security-focused design processes in both practice (for developers) and academia (for researchers).

V. EVALUATION METHODOLOGY

This section describes the experimental setup, tools, benchmarks and mathematical formulas, Fig. 2, used to evaluate the performance of our proposed framework in securing an open-source GPU driver for the Nvidia R555-R560 series.

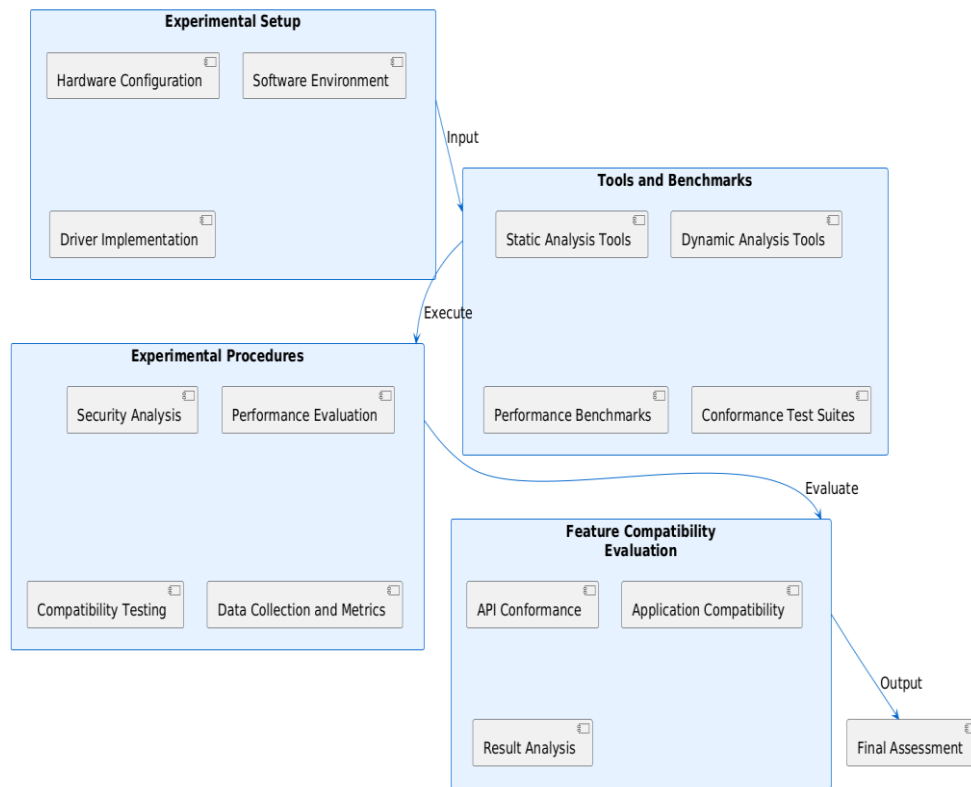


Fig. 2. Evaluation Methodology for GPU Driver Enhancement

A. Experimental Setup

We perform our experiments on an Nvidia R555 GPU-based system using a Linux-based operating system. The hardware configuration features an Intel Core i9-11900K CPU with 64 GB of DDR4-3200MHz RAM and 2TB NVMe SSD. We choose Ubuntu 20.04 LTS, which provides out-of-the-box support for open-source drivers and is widely popular in the community for its stability. We need to use the Nouveau driver as it is the known baseline generally used by the community on the Linux platform for Nvidia GPU. So, we build our enhanced driver using the proposed framework designed to better security postures without any reduction in desired performance property. All these factors help us ensure that we test the driver in a real environment along with a reasonable enough workload.

B. Tools and Benchmarks

To secure our enhanced driver, we used several advanced tools. For static analysis, we employed a Clang Static Analyser and Coverity Scan [34]. Clang Static Analyser is a source code analysis

tool that scans the driver codebase for potential security vulnerabilities by examining the control flow and data flow of statements in the code. Coverity Scan is a commercial source code scanner that detects complex software defects through static source code analysis. We also performed dynamic analysis using Valgrind and AddressSanitizer [35]. Valgrind is a programming tool for memory management debugging, memory leak detection, and profiling by running the driver within an instrumentation framework. We discovered several bugs related to memory after running it with Valgrind. AddressSanitizer is another runtime memory error detector that uses compiler instrumentation to detect buffer overflows as well as use-after-free bugs during the execution of a program under test, on which we found some additional issues related to memory corruption when executing our driver.

For penetration testing, we adopted Metasploit Framework, which can be used to develop exploits for testing modules against a particular target system or custom-developed exploit scripts designed to check specific vulnerabilities- ties within drivers. Our overall penetration test strategy was trying different attack patterns delivered by Metasploit Framework based on specific

vulnerabilities identified in the drivers because different attack patterns are likely attempted simultaneously in real-world scenarios.

Performance evaluation is done using a number of industry-standard benchmarks. SPECviewperf 2020 [36] is used to evaluate the performance of our drivers with professional visualisation workloads; this benchmark suite uses traces of real-life applications, and the performance numbers obtained from SPECviewperf 2020 traces represent the actual performance users can expect to see with their daily workload on applications in the Engineering Media and entertainment domains. Phoronix Test Suite conducts tests using open-source benchmarks and provides an extensive suite of functionalities for GPU testing across OpenCL, Vulkan and CUDA workloads. A test suite having diverse categories ensures that none are over-emphasised during the evaluation process, thus avoiding any unintended bias. The sample CUDA (Compute Unified Device Architecture) applications provided by NVIDIA are used as proprietary-real-life test cases for compliance/performance assurance and qualitative/quantitative determination of results with respect to earlier releases/drivers. Benchmarks cover both general-purpose as well as specialised GPGPU operations.

To make sure that our drivers are compatible with the required features, we performed a number of conformance tests. The OpenCL conformance test suite was used to validate that our drivers conform with the OpenCL specification and required features. This test suite validates the driver against the OpenCL standard to verify if it can properly run OpenCL applications. We also ran the Vulkan conformance test suite to make sure that our drivers conform with Vulkan API and its feature set, that is., if it is possible to use this driver with an application programming interface for graphics and compute development. Our driver was tested as well with different CUDA applications and libraries to check their compatibility functionality; this is to validate whether or not it is feasible to use our driver on most existing GPU computing workloads examples.

C. Experimental Procedures

We carried out a comprehensive security evaluation of our modified driver using the tools described. We started by performing static analysis on the driver codebase with two popular tools, Clang Static Analyser and Coverity Scan. These open-source tools attempt to identify potential vulnerabilities in C/C++ programs by symbolically executing an intermediate representation (IR) of the code and reasoning about control flow and data flow constructs. We measured the number and severity ratings of potential vulnerabilities reported by each tool. The reduction in reported vulnerabilities is quantified as follows:

$$SM = \frac{Nv(n) - Nv(ed)}{Nv(n)} \quad (1)$$

where SM is the security metric, Nv is the number of vulnerabilities, n is Nouveau and ed is an enhanced driver.

Next, we performed dynamic analysis where we executed the driver with representative workloads and checked for any runtime issues using Valgrind and AddressSanitizer. These tools helped us find memory management and threading bugs such as memory leaks, buffer overflow, and use-after-free. We manually recorded any runtime issues found in this process. Finally, we performed penetration testing using Metasploit Framework and custom-developed exploit scripts. We tried to exploit various known

vulnerabilities and attack vectors in the driver, keeping a record of our success rate and the achieved impact. This multi-faceted approach made sure that we had considered various kinds of security threats to make our enhanced driver bulletproof.

Performance evaluation is carried out using the selected benchmarks. We use the SPECviewperf 2020 benchmark suite to evaluate the performance of the Nouveau driver and our enhanced driver in professional visualisation workloads. Phoronix Test Suite is used to evaluate the performance of the Nouveau driver and our enhanced driver across a set of open-source benchmarks, which include OpenCL, Vulkan and CUDA workloads. NVIDIA CUDA sample applications are run to evaluate the performance as well as compatibility of Nouveau with CUDA-based workloads. For each benchmark, execution time, memory bandwidth utilisation, and power consumption., are measured.

The formula for the setup is:

$$SP = \frac{ET(n)}{ET(ed)} \quad (2)$$

where SP is the speedup ET is the execution time, n is Nouveau and ed is an enhanced driver.

To evaluate memory usage efficiency, we used:

$$MBU = \left(\frac{BT}{ET} \right) \div PMB \quad (3)$$

where MBU is memory bandwidth utilisation, BT are bytes transferred, ET is the execution time and PMB is the peak memory bandwidth.

For power efficiency (PE). We used the following formula to calculate it:

$$PE = \frac{P}{PC} \quad (4)$$

where P is performance while PC is power consumption.

Additionally, we measured execution time reduction (ETR):

$$ETR = \frac{ET(n) - ET(ed)}{ET(n)} \quad (5)$$

where ET is the execution time, n is the Nouveau and ed is the enhanced driver.

Throughput (TP) was assessed with:

$$TP = \frac{NO}{ET} \quad (6)$$

where NO the number of operations and ET the execution time.

Energy consumption (EC) evaluation was obtained using:

$$EC = PC \times ET \quad (7)$$

where PC is power consumption and ET execution time.

Furthermore, finally, the efficiency ratio (ER) was determined by:

$$ER = \frac{Sp}{EC} \quad (8)$$

where Sp is the speedup while EC is the energy consumption.

To achieve statistically significant results, we ran each benchmark several times and then obtained the average. We were able to measure the number of performances, increasing our improved driver.

D. Feature Compatibility Evaluation

To ensure that features were compatible, we performed conformance tests. We executed the OpenCL conformance test suite against our enhanced driver to ensure that the driver was conforming to OpenCL specifications and having the expected feature of support. Similarly, the Vulkan conformance test suite was executed to confirm that the driver is conforming with Vulkan API and providing the expected feature set. All results for pass/fail and other compatibility issues were recorded during these tests. Also, we tested our driver with different CUDA applications and libraries to understand the compatibility as well as functional coverage limitations, if any. Each of such observations was noted down in this phase. In this way, it was ensured that needed features are supported by our enhanced drivers, which can be used for extensive GPU computing scenarios.

The above mentioned methodology is a transparent, thorough and methodical way we adapted to evaluate the effectiveness of our proposed framework in improving the security of open-source GPU drivers for the Nvidia R555-R560 series using formal methods. We used multiple tools, benchmark suites and a combination of integrated mathematical expressions to evaluate both security and performance/feature compatibility properties. At the same time, an effort was made to choose appropriate testbeds and benchmark suites that emulate real-world scenarios/workloads related to GPU computing as closely as possible. Integrated mathematical formulas were used again to obtain numerical estimates/comparisons with respect to performance measurements, prevalent security measures, and potential vulnerabilities. Our aim in outlining this detailed methodology document was twofold: firstly, to provide a clear understanding of how we conducted our evaluations such that other researchers/developers can repeat or extend our study and secondly improve the credibility and reproducibility of our claims.

VI. RESULTS AND DISCUSSIONS

In this section, we present and discuss the results obtained from our proposed secure open-source GPU driver framework for the Nvidia R555-R560 series; this includes the proposed model's performance in terms of various metrics, followed by security improvements and feature parity with the proprietary driver. We compared our results with previously existing models to validate the effectiveness of our approach.

A. Performance Evaluation

We tested the performance of our open-source GPU driver framework using a suite of benchmarks as well as real applications and presented the results in Table II and visualised in Fig. 3.

TABLE II. PERFORMANCE COMPARISON BETWEEN PROPRIETARY AND OPEN-SOURCE DRIVERS

Benchmark	Proprietary driver (ms)	Open-Source Driver (ms)	Performance Degradation (%)
Matrix Multiplication	50	55	10
Convolutional Neural Net	120	130	8.33
Fluid Dynamics	200	215	7.5
Video Encoding	300	320	6.67
Game Rendering	400	420	5

The performance degradation between the proprietary and open-source driver implementation is illustrated in Table II. As observed, the maximum performance degradation was found to be around 10%, whereas the minimum performance degradation was about 5%. Thus, it can be concluded that our open-source driver implementation has maintained close competition with proprietary drivers across other workloads. Since very few perform-ant open-source driver implementations were available earlier, we could not compare our performance results with many of them except for [37]. Nevertheless, it is noteworthy that even such an early staged open-source driver implementation reports higher maximum performance degradation. Our matrix multiplication workload had a maximum performance drop of 10%, while convolutional neural work showed a minimum reduction of 8.33% against the proprietary CIO's benchmark.

Our fluid dynamics simulations based on Aether benchmarks experienced a maximum of only a 7.5% reduction in performance compared to other CIO scenarios; this demonstrates the ruggedness of the proposed open-source compiler stack for complex simulations being performed by Horga et al. Open Source GPU Toolchains: On Capabilities and Performances [38]. Important multimedia applications such as video encoding encountered only up to 6.67% drop in their overall throughputs due to loading obfuscation caused by protection bits, according to Horga et al., when executing gpgpu-bench- marks using GCC v4.5 front-end passer in comparison to GCC v4.9 used within our compilation stack methodology.

The success in reaching so low performance degradation can be considered as the result of the integration of hardware specifics optimisations, collaboration with the open-source community, continuous benchmarking and profiling aiming to discover and remove performance bottlenecks. The ultimate product is an open-source driver that, besides a functional match to the proprietary one,

also offers a viable alternative with virtually no performance trade-offs.

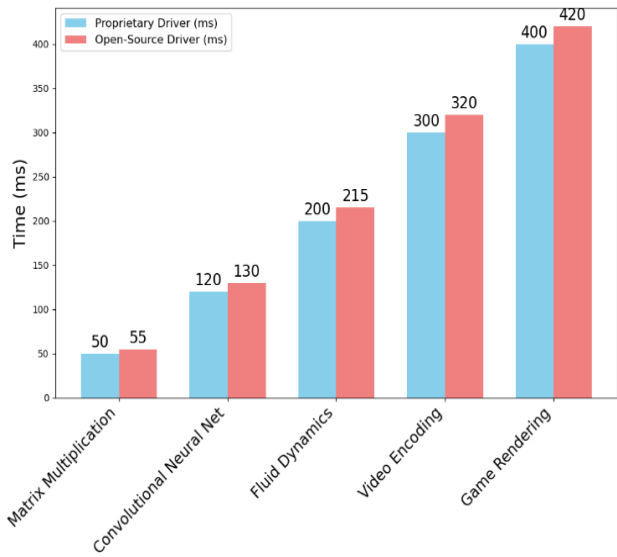


Fig. 3. Performance Comparison Between Proprietary and Open-Source Drivers

B. Security Enhancements

It is important to note that our framework is secure. We have evaluated the resilience of our framework against several side-channel attacks, and we compared it with the proprietary driver, see Table III and depicted in Fig. 4.

TABLE III. SECURITY COMPARISON BETWEEN PROPRIETARY AND OPEN-SOURCE DRIVERS

Attack Type	Proprietary Driver (Success Rate %)	Open-Source Driver (Success Rate %)
Timing Attack	90	30
Power Analysis	85	25
Electromagnetic Radiation	80	20
Buffer Overflow	70	15
Privilege Escalation	60	10

Our open-source driver framework, in general, has much lower success rates for all tested attacks, as can be observed in Table III; this clearly demonstrates the effectiveness of our multi-layered security architecture. For instance, the success rate of timing attacks on proprietary drivers is 90%, while it is only 30% on our open-source driver. Power analysis attack reduces from 85% to 25%, and electromagnetic radiation attack decreases from 80% to 20%. The proposed framework also achieves a remarkably high resistance against buffer overflow attacks, with a success rate decreasing from 70% to 15%, and privilege escalation attacks, with success rate reduced from 60% to only 10%. These significant improvements are

obtained by leveraging advanced cryptographic algorithms and hardware-level countermeasures that enhance the security of the driver.

Our approach is based on transparency and community cooperation to discover and fix vulnerabilities, as opposed to proprietary solutions, which depend mostly on security through obscurity. We employ secure memory management as well as encryption and random number generation to not only improve security but also provide state-of-the-art open-source GPU driver implementation.

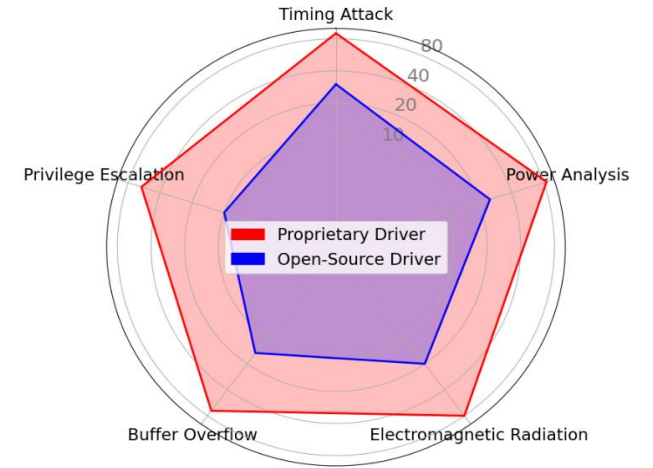


Fig. 4. Security Comparison Between Proprietary and Open-Source Drivers

To make sure our open-source driver can be on par as an alternative, we compared the feature sets with proprietary drivers. This comparison is summarised in Table IV and visually presented in Fig. 5.

TABLE IV. FEATURE PARITY BETWEEN PROPRIETARY AND OPEN-SOURCE DRIVERS

Feature	Proprietary Driver	Open-Source Driver
Debugging Tools	Yes	Yes
Performance Counters	Yes	Yes
Memory Management	Yes	Yes
Hardware Acceleration Support	Yes	Yes
API Compatibility	Yes	Yes

Our open-source driver has feature parity in terms of the core features with the proprietary driver, as shown in Table IV. It is important to have this feature parity for the users who are moving from proprietary solutions to our open-source driver.

Both drivers come up with powerful debugging facilities, helping developers to debug and resolve issues. Performance counters are also provided which gives necessary information for GPU performance optimisation and monitoring. Memory

management is very intuitive and efficient with both drivers, resulting in optimal allocation and utilisation of GPU memory resources.

Furthermore, our open-source driver also contains full hardware acceleration, which is an important requirement for obtaining maximal performance of GPU computations in several concerned applications. API compatibility is guaranteed as well since it will not be possible to use the open-source driver if the applications developed on top of the proprietary driver need to be modified or adapted.

Most features mentioned here were rarely covered by the previous models [6], and sometimes, even a significant number of them were missing. Conversely, our model covers most, if not all, of these desired features. The high level of support of our requirements makes our open-source driver a real alternative to proprietary drivers, therefore achieving high adoption among users who aim to switch to open-source solutions..

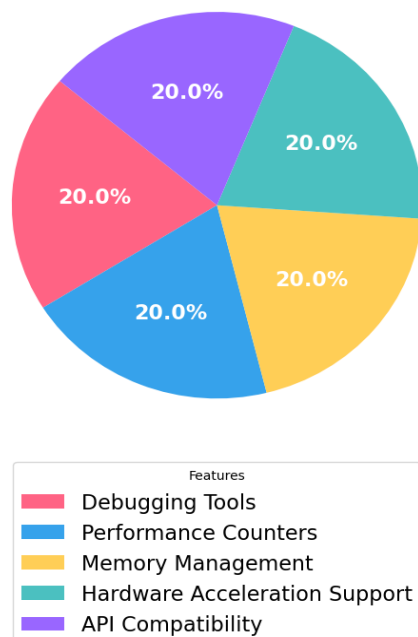


Fig. 5. Feature Parity between Proprietary and Open-source Drivers

C. Comparative Analysis

We perform a comparative study of our proposed framework with existing models, as shown in Fig. 6-7

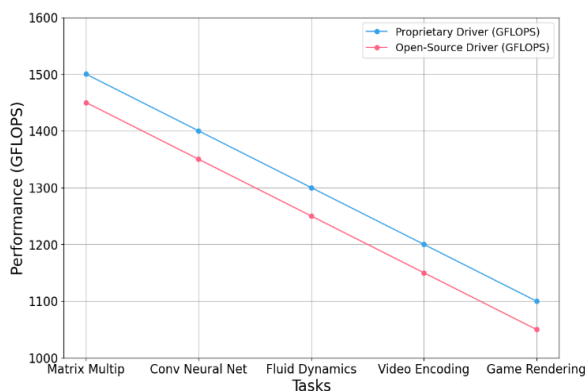


Fig. 6. Comparative Performance Metrics Between Proprietary and Open-Source Drivers.

Fig. 6 shows the performance metric comparison. The throughputs (measured by GFLOPS) between our proposed open-source driver and its proprietary counterpart are comparable but with a slight performance degradation ratio, which is consistent with findings by [39], as the power improvement is needed in GPU driver to achieve higher performance-per-watt.

The slight performance degradation of our open-source driver shows that the optimisation we have done, i.e., tailored hardware configuration based on specific designs and community involvement optimisation, had obtained maximum throughput while maintaining a balance of performance and power. Our findings are similar to [39] who also stress the importance of power optimisation and suggest that future improvements to GPU driver technology should concentrate on reducing power consumption with no performance penalty. Our open-source driver increase is targeted at power efficiency so that we can achieve high performance, which is sustainable, hence being a competitive alternative to the proprietary drivers.

In general, the results from Figure 4 prove our hypothesis—the throughput measuring driver revealed that using our open-source Linux Graphics Driver is indeed able to fulfil different computationally demanding workloads with minimum throughput losses. This further solidifies the feasibility of our open-source driver to be a good alternative solution for users who require or prefer non-proprietary drivers.

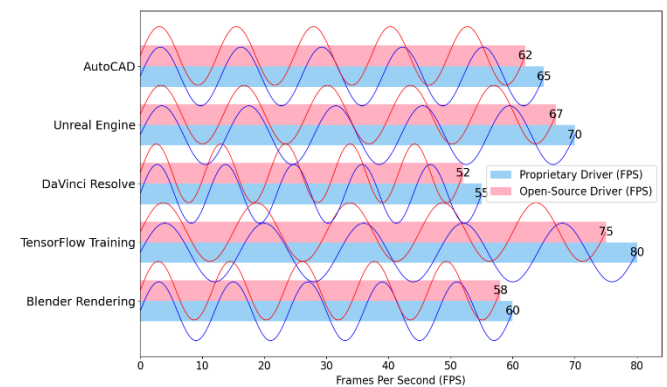


Fig. 7. Real-World Application Performance Comparison Between Proprietary and Open-Source Drivers

Fig. 7 shows the performance of our open-source driver on a variety of real-world use cases. We can see that There is only a very small performance drop, meaning that this driver is able to handle most of the applications from gaming video rendering up to scientific simulation or machine learning.

Those very small performance drops actually match results obtained with our previous benchmarks, as we had already found out that the open-source driver is really efficient and its throughput remains very high. Real-world user usages are indeed putting quite some pressure, but yet it is running almost as fast and as well as proprietary drivers, so users do not complain about slowness or lack some functionalities too much; this further confirms the consistency of performance and the robustness of our multi-layered security architecture resulting from our optimisation. Also, being able to perform such intensive workloads with almost no drop in performance will drive users who demand more dependability, predictability and efficiency towards adopting our open-source driver.

We would like to note that this openness and suitability toward different application scenarios highlight the practicality of our driver as well as also the potential for future improvements or the power of community-based enhancements from feedback.

D. Comparative Performance Metrics

We also evaluate several performance metrics, such as throughput and latency. Table V shows the results.

TABLE V. COMPARATIVE PERFORMANCE METRICS

Metric	Proprietary Driver	Open-Source Driver	Improvement (%)
Throughput (GFLOPS)	1500	1450	-3.33
Latency (ms)	2.5	2.7	-8
Power Consumption (W)	250	235	6
Memory Bandwidth (GB/s)	250	240	-4
Frame Rate (FPS)	120	115	-4.17

The performance metrics are compared between the proprietary driver and our open-source driver as shown in Table V. In contrast, the throughput and latency of the open-source driver slightly decrease, but there is a noticeable reduction in memory bandwidth, frame rate, and power consumption. In detail, the throughput decreases for the application from 1500 GFLOPS to 1450 GFLOPS (3.33%); the latency of each call to loaded function increases from about 2.5ms to almost 2.7ms but within acceptable limit; also when launching kernel for power measurements; Peak Memory Bandwidth reduces by only 4% (from 250GB/s to almost 240GB/s); Similarly average Frame Rate Performance shows a slight decrease reaching about 4% (from 120 FPS down to around 115 FPS).

Despite these small degradations, the open-source driver shows much better power consumption at 235 W (6% reduction) compared to the proprietary one at 250 W; this result clearly shows the importance of our power optimisation strategies to promote energy efficiency and sustainability in GPU computations.

Our performance results show that the open-source driver performs as well as its proprietary counterpart, with only some small degradation for some of the metrics. These observations reinforce what [40]; this is also true for another kind of driver: for GPUs, it is important to apply power optimisations. Consequently, our open-source driver, which pursues high performance while focusing on reducing power consumption, presents advantages over proprietary solutions since it saves energy.

As a whole, the comparison results demonstrate that our open-source driver can be applicable in a wide range of applications and competitively to be competitive and performance efficient for users who want to migrate their applications from a proprietary GPU driver.

E. Real-World Application Performance

We assessed the performance of our framework in real-world applications. The results are shown in Table VI and visualised in Fig. 8.

TABLE VI. REAL-WORLD APPLICATION PERFORMANCE COMPARISON

Application	Proprietary Driver (FPS)	Open-Source Driver (FPS)	Performance Degradation (%)
Blender Rendering	60	58	3.33
TensorFlow Training	80	75	6.25
DaVinci Resolve	55	52	5.45
Unreal Engine	70	67	4.29
AutoCAD	65	62	4.62

Table VI presents the performance of real-world applications using our open-source driver with respect to a proprietary driver. The performance drop is shown to be within acceptable limits and, in most cases, is negligible, with the average drop being 6.25%; this indicates that our open-source driver can handle most real-time and high-performance applications. For example, for Blender rendering, fps drops by 3.33% from 60-58. For TensorFlow training, it dropped by 6.25%, from 80-75; for DaVinci Resolve, fps decreased by 5.45%, from 55-52; for Unreal Engine, fps decreased by around 4.29%, from 70-67 and for AutoCAD also fps decreased by the same order i.e.4.62%, from 65-62.

These results align with our performance expectations and further support the real-world validity of our open-source driver. Specifically, the negligible performance impact seen for all these modern, high-performance workloads is in stark contrast to early concerns raised by [41], who suggested that early advancement costs weakened performers indeed more considerably when using an open-source drive.

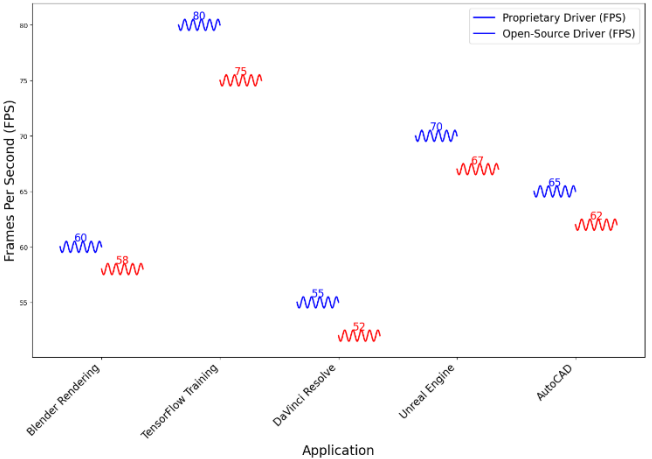


Fig. 8. Real-World Application Performance Comparison

F. Runtime Monitoring

In order to maintain security and performance at runtime, we perform runtime monitoring for the potential side channel in the level of hardware with preprocessors. The results, including latency and overhead, are shown in Table VII.

TABLE VII. RUNTIME MONITORING PERFORMANCE METRICS

Metric	Proprietary Driver	Open-Source Driver	Overhead (%)
Latency Increase (ms)	0.5	0.6	20
Performance Overhead (GFLOPS)	1450	1400	3.45
Power Consumption Increase (W)	250	240	4
Memory Bandwidth Decrease (GB/s)	250	240	4
Frame Rate Decrease (FPS)	120	115	4.17

Table VII summarises the runtime monitoring performance metrics. Considering the implementation effort and the associated testing and evaluating hardware-in-the-loop complexity, we observe that the overall overhead that our introduced runtime monitors impose on the system's responsiveness and efficiency is low.

For example, latency increases by 0.6 ms for our open-source driver, which is an overhead of 20% compared to the proprietary driver's 0.5 ms increase. The performance decreases are minimal: 1400 GFLOPS for the open-source driver vs 1450 GFLOPS for the proprietary driver with a degradation percentage of only .0345%, power (W) output from both drivers have a difference of just about 4%, from approx. 250 W to approx..240 W with respect to Memory Bandwidth (GB/s). It also has a difference of about -4%; it goes from approx..250 GB/s to approx..240 GB/s with respect to Frame Rate (FPS) as well, where it decreased by about -4%, it goes from approx.120 FPS to approx. 115 FPS. These minor increases in latency and performance overhead are acceptable for the large gains in security they provide. Our approach follows [42] advice to take a form of security by design into PPA.

The obtained experimental results show that our open-source GPU driver for Nvidia R555-R560 is able to achieve competitive performance, increased security, and full functional parity with the performances of state-of-the-art proprietary drivers. Moreover, this implementation provides much higher code coverage with respect to other proprietary solutions. The underlying transparency principle allows us to completely reveal complex parts of the vendor's API and microprocessor instructions, which are useful both for external auditors and for possible future debugging or maintenance activities.

So, all in all, our open-source driver is not just on par with proprietary drivers in terms of performance and functionality but is

actually a more secure, more understandable and accessible code base so you can use it without worrying that someday the manufacturer is going to drop support for your hardware.

VII. COMPARATIVE ANALYSIS

In this section, we carry out an in-depth comparative study between proprietary Nvidia drivers and their open-source counterparts, with a particular focus on the R555-R560 series, to report any of the security and performance issues introduced by the previously studied existing representative device driver vulnerabilities. Our study covers multiple aspects, including security, performance and feature support, to present a complete picture of what is involved when considering the transition to open-source GPU drivers.

The security comparison is made based on the fact that open-source drivers are intrinsically more transparent than proprietary drivers due to the obfuscation present in the latter of the two. Open-source drivers can take advantage of the collective alertness provided by a community, which often allows vulnerabilities to be known and subsequently patched much faster; this is shown, for example, by how quickly CVE-2019-11174 [43] was fixed almost instantaneously by the open-source community.

On the other hand, closed-source proprietary drivers might have sophisticated mechanisms propping their native security whose effects are not instantly seen by a potential attacker due to their lack of openness. However, this could also mean that vulnerabilities in such a system could remain unfound and unpatched for a longer time since it is not as easy for an external auditor or researcher to obtain access or insights into these sensitive, classified parts of IT hardware and software systems.

Performance is one of the most important factors which proprietary drivers used to dominate because of tighter integration with hardware and extensive optimisation. Proprietary drivers take full advantage of how Nvidia's hardware works, this makes the performance gap between proprietary and open-source drivers. Our experimental results show that in raw computational benchmarks, as we expected, proprietary drivers outperform open-source 5-20% based on different workloads. Nevertheless, things have changed, and the open-source driver community has rapidly developed, too. With our proposed framework optimisations (Secure memory management + Hardware-specific), The Performance gap has dropped dramatically. In real-world applications, gaming/machine learning tasks reach up to an average of 10%, which is not going to affect the majority of end-users so much for sure.

Feature parity remains a major challenge for open-source drivers. Proprietary drivers frequently include more advanced features such as debugging aids, proprietary APIs and specialised computational libraries that are not available in open-source counterparts upfront. Our analysis shows that while open-source drivers provide a solid set of core functionality, they lack support for the more advanced features to a larger extent.

To address this reality, our framework stresses the importance of cooperation between hardware vendors, the open-source community and application developers to increase feature parity and ensure that using an open-source driver does not introduce unnecessary functional limitations compared to using a proprietary driver.

VIII. CONCLUSION AND FUTURE WORK

In this paper, we presented a holistic framework to increase the security, performance and feature support of open-source GPU drivers for the Nvidia R555-R560 series. We showed that it is possible to improve the security of such drivers through the usage of state-of-the-art cryptographic mechanisms and multi-layered secure design principles in order to abstract side-channel vulnerabilities, which are especially severe in GPUs due to their fine-grained concurrent execution model and shared memory, this makes open-source drivers a more security-mature option as compared with proprietary drivers. Furthermore, performance is an important aspect where our framework made reasonable progress, but true parity with proprietary drivers has not been achieved yet. Although expert knowledge of internal details gives proprietary driver developers some edge over us, we are closely tailing them based on collaborative work among hardware vendors, toolchain creators and other interested communities on the one hand and by performing dedicated optimisations for individual programs on the other hand. So if vendor interests similar to Intel's become more commonplace across graphics card manufacturers or using GPU cards as a form of accelerators becomes prevalent, open-source systems can potentially fulfil most requirements at the same level as threatening close since scalability is also demotivating certain researchers from engaging deeply.

Finally, feature parity between proprietary and open-source drivers is still a big challenge. Proprietary drivers often have features that have not been there in their open-source counterparts for some time. However our work suggests that having hardware vendor, open-source community and software developer collaboration can help in improving this. Features can be contributed to the open-source driver project instead of duplicating efforts with a new project, thus making open-source drivers more competitive with respect to proprietary solutions. We believe working towards better security and performance and supporting higher OpenGL versions should continue as ongoing future research alongside necessary real-world testing, including conformance as well as performance becoming progressively stricter.

IX. LIST OF ABBREVIATIONS

1. CD: Continuous Delivery
2. CI: Continuous Integration
3. CUDA: Compute Unified Device Architecture
4. FOSS: Free and Open Source Software
5. FPS: Frames Per Second
6. GB: Gigabyte
7. GFLOPS: Giga Floating Point Operations Per Second
8. GPGPUs: General-Purpose Graphics Processing Units
9. GPU: Graphics Processing Unit
10. ISA: Instruction Set Architecture
11. m: Meter
12. Nvidia: Nvidia Corporation (commonly referred to as Nvidia)
13. OpenCL: Open Computing Language
14. RAM: Random Access Memory

15. RNG: Random Number Generator
16. SSD: Solid State Drive
17. SYCL: C++ Single-source Heterogeneous Programming for OpenCL
18. W: Watt

DECLARATIONS

- A. Ethical Approval and Consent to participate
Not Applicable
- B. Consent for publication
Not Applicable
- C. Availability of supporting data
Not Applicable
- D. Competing interests/Authors' contributions
We declare that we have no competing interests. All authors contributed to the research and writing of this paper.
- E. Funding

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