**Reviewer: 1**

Recommendation: RQ - Review Again After Major Changes

Comments:

The paper presents a novel mechanism, called Aurora, to enable trusted I/O operations on an untrusted machine by leveraging Intel SGX and System Management Mode. This is an important topic as untrusted I/O operations can compromise the integrity and confidentiality of the data.

== Threat model ==

In their threat model, the authors consider that the hardware and device drivers are trusted but the software stack (including the operating system) is untrusted. While reading the paper I had to remind myself on every page that the drivers are trusted.

In our new version of the article, the drivers is not trusted. We do not trust but verify the behavior of the driver.

Besides the authors write that their "solution focuses on the password security on the client side". I am not entirely convinced by this threat model: Intel SGX is primarily targeted at cloud-based applications, not personal devices on which users plug-in keyboards and usb drives. I would have liked to read a discussion on how this system will be used in practice and what are the use-cases.

Intel SGX is now available on personal laptops and NUCs. Personal passwords are also very important! We discuss this in \subsection{Specific Trusted Paths}.

== Contribution ==

The main assumption of your work is that the hardware and drivers are trusted. The system would rapidly stop being secure if this assumption is broken. I believe this assumption does not hold in practice.

Only HW, Aurora SW inside SMM/SGX is trusted. Drivers are not.

The dedicated counting thread and the thread checking for the content of the I/O APIC table are weak hacks, not a valid solution: you cannot assume that these 2 threads, which need 2 cores and will decrease the performance of your system, will do busy-waiting forever.

The contribution would be more substantial and interesting if these assumptions were removed.

We require the counting thread to be located with the main thread in the same core using Intel Hyper-Threading technology. Such a design eliminates most of the side-channels like Spectre/Meltdown/RIDL, etc.

One obvious solution for secure I/O, never considered by the authors, is to use TLS connections from inside enclaves to contact remote peripherals (e.g., printer, storage). The TaLoS library (cited by the authors) can be used to provide such secure connections.

TaLos would require another TLS endpoint in the remote server. In Aurora, the SMM acts as the proxy that connects with local devices. Physical attacks on these devices are out of scope.

== Case studies ==

In Section VI.B ("Secure OpenSSL Session"), if the trusted time is needed only to obtain a random value then you could instead use the secure random number generator available to Intel SGX (and used by the TaLoS library: <https://github.com/lsds/TaLoS/blob/master/src/talos/patch/arc4random.c.patch#L178).>

Actually, the TLS server needs to provide a timestamp for the expiration time, not for the random number, which is why we need this value from hardware RTC.

In the same section, if the server creates a certificate each time it receives a new connection then how does the client attest that this certificate is correct? This check will probably increase the time needed to open a new connection.

Such a certificate requires a trusted timestamp. A generated certificate can be sealed to the untrusted storage for reuse. We regenerate it repeatedly to measure the efficiency of Aurora’s time services.

In Section VI.C ("Secure SQLite Database"), why do you eliminate the file-related ocalls? How do you provide similar functionalities? E.g., how do you implement `pread`, `pwrite`, `lseek`?

We replace the original file-related ocalls with Tlibaurora’s libc. Pread and pwrite are not used by SQLite.

We need more benchmark, comprehensive.

Why is the use-case based on USB storage and not a more traditional disk storage?

Regarding the experiment at the end of the section, where does the 18% overhead come from? Cryptographic operations or USB access?

Disk can also be supported using Aurora. It has been discussed in previous work such as AuditedIO and Pesos. Instead, we use USB as an example, as it is more common to use USB mass storage on the client side.

At the end of “Trusted USB Storage Benchmark”, we claimed that “The major overheads are contributed by SMM/Protected mode transitions and cryptographic computations on each block”.

== Evaluation ==

It is not clear to me what the authors want to show in their evaluation.

For example I do not understand the experiment of Table II (page 9). What are you expecting? What do you prove? Do you take into account accesses to trusted time when you report a 11% performance overhead to check whether an enclave requests more than 10k smcalls?

Yes, our prototype uses a threshold to block a malicious enclave from abusing more than 10K smcalls.”, as claimed in VIII.A.

Furthermore, according to the first paragraph of Section VIII ("Performance Evaluation") you test your system using virtual machines. Why? How does this affect performance?

We re-run on physical machines now.

Finally, the security evaluation (Section VII) does not convince the reader that your system is secure. What about replay attacks, e.g., if the recorded time values are exchanged (see "Attack-awareness" in Section IV.C)?

It detects attacks as expected. Replays is deemed as rollback of time value.

How do the enclave attest each others? How do you ensure that an application enclave is certain that it is communicating with a correct enclave and not a malicious one trying to impersonate Aurora?

It uses SGX local attestation to do so.

How does Aurora ensure that it is communicating with a valid enclave and not a malicious one trying to impersonate an application?

Aurora’s Mutual Attestation solves this in Section Secure Session Life-cycle.

Is it possible to conduct a buffer overflow attack on the buffer used by the SMRAM to cache keyboard input and thus maliciously access sensitive information?

No. The buffer will be sent back to enclave and cleared and recycled when it’s about to be full. Besides, the data buffer overflow will not cause control flow hijacking. It is easy to detect such overflow. We have ported a hardened allocator named FreeGuard (FreeGuard: A Faster Secure Heap Allocator, CCS ‘17) into SMRAM.

== Related work ==

Here are additional works that might be of interest to the authors:

-ROTE (Matetic et al, "ROTE: Rollback Protection for Trusted Execution", Usenix Security '17) use a distributed protocol to provide monotonic counter to enclaves. Even if it probably has a higher latency than the time service described by the authors, there exists at least one successful implementation ("LibSEAL: revealing service integrity violations using trusted execution", Aublin et al., Eurosys '18)

-SGX-FS (Burihabwa et al., "SGX-FS: Hardening a File System in User-Space with Intel SGX", CloudCom '18) proposes a secure file system that leverages Intel SGX. This is more generic than the secure USB storage mechanism proposed by this paper;

-similarly, Pesos (Krahn et al., "Pesos: Policy Enhanced Secure Object Store", Eurosys '18) leverages Intel SGX to propose a secure object store.

Thanks for the information. All references are now added. Besides, we add more recently published related work, such as Fidelius (IEEE S&P ‘19).

== Other comments ==

The paper could benefit from some reorganization, which would then allow the authors to address the above comments.

-while the title is correct, I do not understand the emphasis on "X86 systems". I would suggest to remove this term and rename the paper, e.g., to "Establishing Trusted I/O Paths on Intel SGX-based Systems";

-section II.C ("Trusted I/O Paths") does not bring anything to the paper;

It is an introduction of new concept, for readers to better comprehend our work.

-same for the second paragraph of Section V.A ("SMM Supervisor and Drivers");

-the ashmd module is never clearly defined;

It is described in “ashmd Kernel Module” in III.E 1).

-in Fig. 1 the UEFI drivers box should not be gray as they are trusted.

They are untrusted but verified.

The paper contains several English mistakes:

-page 3, "forth" -> "fourth";

-page 4, "these drivers are lack" -> remove "are";

-page 6, "as to the hardware clock" -> replace "to" by "for";

-page 7, "encalve" -> "enclave";

-page 9, "with as less noise" -> replace "less" by "little";

-etc.

All are corrected. Thank you!

Additional Questions:

1. Is the topic appropriate for publication in these transactions?: Adequate Match

1. Is the paper technically sound?: Yes

2. How would you rate the technical novelty of the paper?: Somewhat Novel

3. Is the contribution significant?: Incremental

4. Is the coverage of the topic sufficiently comprehensive and balanced?: Treatment somewhat unbalanced, but not seriously so

5. Rate the Bibliography: Satisfactory

1. How would you rate the overall organization of the paper?: Could be improved

2. Are the title and abstract satisfactory?: No

3. Is the length of the paper appropriate? If not, recommend what should be added or eliminated.: Yes

4. Are symbols, terms, and concepts adequately defined?: Yes

5. How do you rate the English usage?: Needs improvement

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**Reviewer: 2**

Recommendation: AQ - Publish With Minor, Required Changes

Comments:

\* Paper summary

The paper presents Aurora architecture for trusted I/O paths for enclave applications on Intel platforms with SGX and SMM support. Specifically, the paper outlines design for securing communication with a keyboard, printer clocks, and storage in the presence of an untrusted OS. By default, Intel SGX does not guarantee secure interface to devices, and Aurora bridges this gap for applications where it is essential to have a trusted path to one or more I/O devices. The authors make use of SMM which is protected from the OS to communicate with these devices over a trusted channel.

\* Strengths

- Good observation about the use of SMM for securing I/O communication.

- Well-detailed design and discussion of corner cases for attacks.

- The evaluation is well executed with a good effort to account for many of the design choices made by Aurora.

\* Detailed comments to the authors for minor revision

- Lacks secure display support by design, which makes the appeal of Aurora's standard architecture for secure IO weaker. Network paths are never mentioned in the context of I/O operations.

Display is not addressed in Aurora because the image frame (video) needs real-time transfer. Network is not considered as we can simply use TLS inside enclaves as both ends. Why we improve storage is that SGX is vulnerable to replay attacks, and the storage device cannot detect this, so we use SMM as a trusted proxy.

- Orthogonal techniques can also bridge the same gap, albeit in bits and pieces, so the novelty of Aurora is incremental.

Yes, Aurora propose a novel architecture without modifying the system software.

- The design for keyboard input protection is weak. Blinking caps lock key to notify the user that the login screen is not being forged is not user-friendly. But more glaringly, a random integer from the interval of [1, 5] simply does not have enough entropy. The attacker can also blink the caps lock key for a randomly picked value between [1, 5] and can be correct with very high probability. The authors need to address this with a substantially secure method.

Thank you for pointing that out! We then use an improved approach from TrustLogin (AsiaCCS ‘11). At the beginning when the computing is not connected to the network (when the compromised kernel is not possible), we allow the user to use enclave to control SSV to program the PC speaker, the user can choose any music he/she wishes. After that, the user connects to the network in the danger of cyber attacks. He/She uses the prior knowledge pre-shared with the SSV to know if the trusted path is built.

- The threat model is unclear and keeps changing while discussing the design in Section 4. For example, the security boundary of the printer I/O ends at the SMM is not really an end-to-end secure channel from the enclave to the end device. Same is the case for the keyboard, where the adversary can physically tamper with the keyboard device to extract keystrokes. It is fine if the design does not protect against these scenarios because it involves an on-premise adversary, but they cannot be excluded from the discussion in the paper.

Yes, the paper mainly addresses the attacks from compromised system, where physical attacks on hardware is not considered. We have reclaimed this in the threat model.

- In Section III-E (page 5, column 2, last para), strong claims about cache side channel freedom merely because of AES-NI, especially in Intel SGX setting are misleading and self-contradictory to the threat model which rules out all side-channels.

We complement this in the threat model part: “Even thought we do not consider physical attacks on devices, side-channel attacks, or denial-of-service attacks, we adopt side-channel free cryptographic algorithms and apply an oblivious packet transferring method between hardware enclaves.”

- Any encryption scheme for integrity such as AES-GCM will have MAC data apart from the encrypted content. Nowhere in the paper did I see the discussion about where this metadata is stored.

MAC is encoded as part of the packet, and is transparent to the developers.

- The claim for defense against Iago attacks is not well explained. It is unclear how Aurora can detect mapping attacks without keeping any information about the memory allocation system.

We adope LibOS method for memory mapping, which is a shim layer to verify the result of untrusted calls. We added how Aurora detect mapping attacks.

- The "Verification Module" discussed in Section III-C does not verify the correctness of the return values, it merely sanitizes the values by checking if they are within the valid range of error codes.

Yes it does. We add this.

- It is unclear if the design choice of disconnecting the secure session is useful in terms of performance, because it highly depends on how frequently the application uses the I/O paths. It is unclear how / when Tlibaurora decides to notify SSV for termination.

As soon as the trusted app is terminated, Tlibaurora decides to notify SSV for termination. Our evaluation shows that the performance is not evident, as Aurora’s trusted services are requested on demand.

- The evaluation of SQLite only performs insert operations and excludes other DB operations which exhibit a very different file IO behavior. Thus the overhead numbers are not representative of a real workload.

We added a comprehensive evaluations on SQLite (Benchmark) in VI.C.

- The use cases are not well motivated because it is not impossible to deploy them in the absence of Aurora. The OpenSSH and OpenSSL examples can be deployed without support for keyboard-based username password authentication by forcing PKI-based authentication. For cases where the enclave logic may need a username and password, it can receive it over a secure network or via sealed data in the form of files. Further, as the authors themselves mention, the only use of timers in OpenSSH and OpenSSL is for generating randomness which can be addressed by Intel's support for a secure source for randomness for enclaves. For timeouts, the enclave can use secure clocks built on monotonic counters. Thus, the argument that Aurora is vital for execution of these applications is not compelling.

We are targeting a local personal computer where the system can still be compromised, so the secure network cannot be applied. Yes the sealed file is a good idea, but for the first time user inputs his/her password, he needs a trusted path between the keyboard and the target enclave (maybe a browser enclave). For highly frequent network I/O, to protect from replay attacks, we need high-precision clock, which current SGX trusted clock and monotonic counters cannot offer.

We need a better app.

- The storage cheat attack example in Section VII raises concern about the threat model as mentioned earlier. After reading the para in Section VII, it seems that Aurora is attempting to detect when the kernel driver drops the I/O requests which is a form of DOS. While it may be advantageous to detect such DOS-like evasion by the kernel driver whenever possible, it is misleading to classify it under the storage attack. Mainly because there are so many DOS- like attacks at the storage interface which Aurora cannot detect.

Yes. Although there are many, Aurora can be used to check the consistency and provide auditable proof.

- The intro and the middle sections paint a picture that there is not a single existing solution for secure IO, which is misleading. Consider mentioning Intel's PAVP and trusted monotonic counters which are well-known solutions in the earlier sections. They can then be dismissed as point-wise solutions as opposed to a generic solution to I/O.

Good idea. We reorganize them to make it better. We highlight these methods in the Intro.

Although some are addressed by newly released Intel SGX platform, as Intel ME supports these channels to enclaves, but they are case by case and not general at all.

- Minor fixes

-- Page 1, Column 2, Para 3: incomprehensible opening sentence. Done

-- "time cheat attacks and storage cheat attacks: consider replacing cheat with "deception? Great.

-- Use output instead of "outputted". Done

-- The claim about running 56 enclaves is wrong because (a) the enclave may need more than 1MB of heap+stack memory depending on the code executing inside the enclave (b) the SSV also may need larger heap sizes apart from the code size.

Yes, we give up on claim that.

-- The performance overhead for OpenSSH is not mentioned in the paper.

The login overhead is around +13% for each keystroke.

-- The figures are referred to on a different page than they appear on.

We adjusted these, and make them near the graph.

-- The discussion in Section VII is not Security Evaluation and can be merged without Section VIII as practical effectiveness of Aurora.

-- It is unclear if the ashmd driver is custom written for Aurora or is something that already exists on Linux platforms. Please clarify for ease of reading.

Sure! It is particular for Aurora.

-- Consider changing the para title "Verification Module" to Sanitization / Validation module.

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