Linux* Stacks for Intel® Trust Domain Extension 1.5

v0.1

September 2023

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Revision History

Revision Number	Description	Date
0.1	Initial Version	21th September 2023

1 Introduction

1.1 Overview

Intel® Trust Domain Extension (Intel® TDX) refers to an Intel technology that extends virtual machine extensions (VMX) and Intel® Total Memory Encryption – Multi-Key (Intel® TME-MK) with a new kind of virtual machine guest called a trust domain (TD). A TD runs in a CPU mode that is designed to protect the confidentiality of its memory contents and its CPU state from any other software, including the hosting virtual machine monitor (VMM) [1]

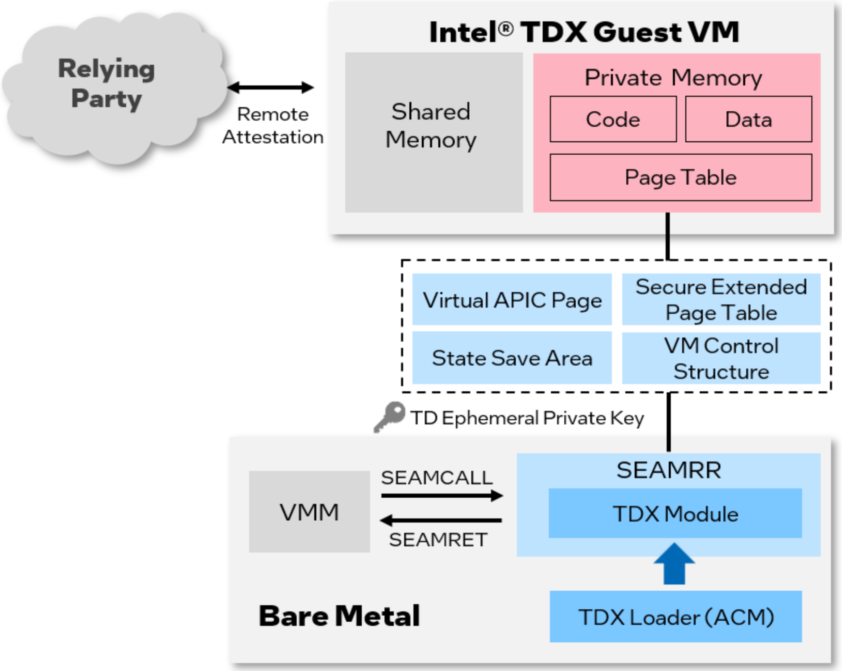
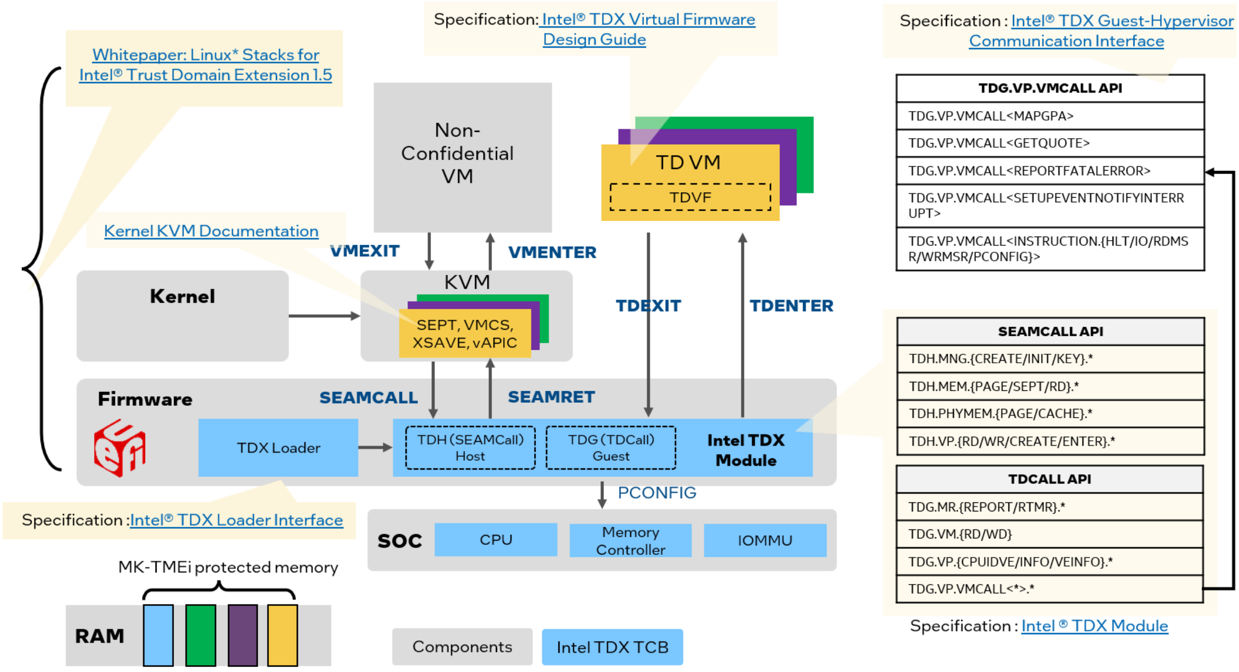


Figure 1: Intel® TDX

The white paper or specifications for Intel TDX can be found at [Intel® Trust Domain Extensions](), the major component interfaces are defined in the specifications in Figure 2: Intel TDX Component Interfaces.



TDG.VP.VMCALL API
TDG.VP.VMCALL<MAPGPA>
TDG.VP.VMCALL<GETQUOTE>
TDG.VP.VMCALL<REPORTFATALERROR>
TDG.VP.VMCALL<SETUPEVENTNOTIFYINTERRUPT>
TDG.VP.VMCALL<INSTRUCTION.{HLT/IO/RDMSR/WRMSR/PCONFIG}>

SEAMCALL API
TDH.MNG.{CREATE/INIT/KEY}.*
TDH.MEM.{PAGE/SEPT/RD}.*
TDH.PHYMEM.{PAGE/CACHE}.*
TDH.VP.{RD/WR/CREATE/ENTER}.*

TDCALL API
TDG.MR.{REPORT/RTMR}.*
TDG.VM.{RD/WD}
TDG.VP.{CPUIDVE/INFO/VEINFO}.*
TDG.VP.VMCALL<*>.*

Figure 2: Intel TDX Component Interfaces

Linux* Stacks for Intel® TDX is an end-to-end hypervisor cloud stack that includes Infrastructure as a Service (IaaS) and Platform as a Service (PaaS) components to produce the following minimal use cases:

- Launch Intel® TDX guest VM to run general computing workloads.
- Do launch-time measurement within the Intel® TDX guest VM.
- Do runtime attestation with the quote generated by Intel® Software Guard Extensions (Intel® SGX)-based quote generation service (QGS) on the IaaS host.

Linux* Stacks for Intel® TDX 1.5 can run on both Sapphire Rapids and Emerald Rapids platforms. Compared with Linux* Stacks for Intel® TDX 1.0, it adds the following new features.

- TD live migration – it allows to migrate a running TD from source platform to destination platform.
- TD preserving – it allows an existing TD to keep running unmodified after a TDX module update.
- vTPM solution – it provides a virtual TPM 2.0 compliant device for TDVM. It works with tpm2-tools, IMA and Keylime.

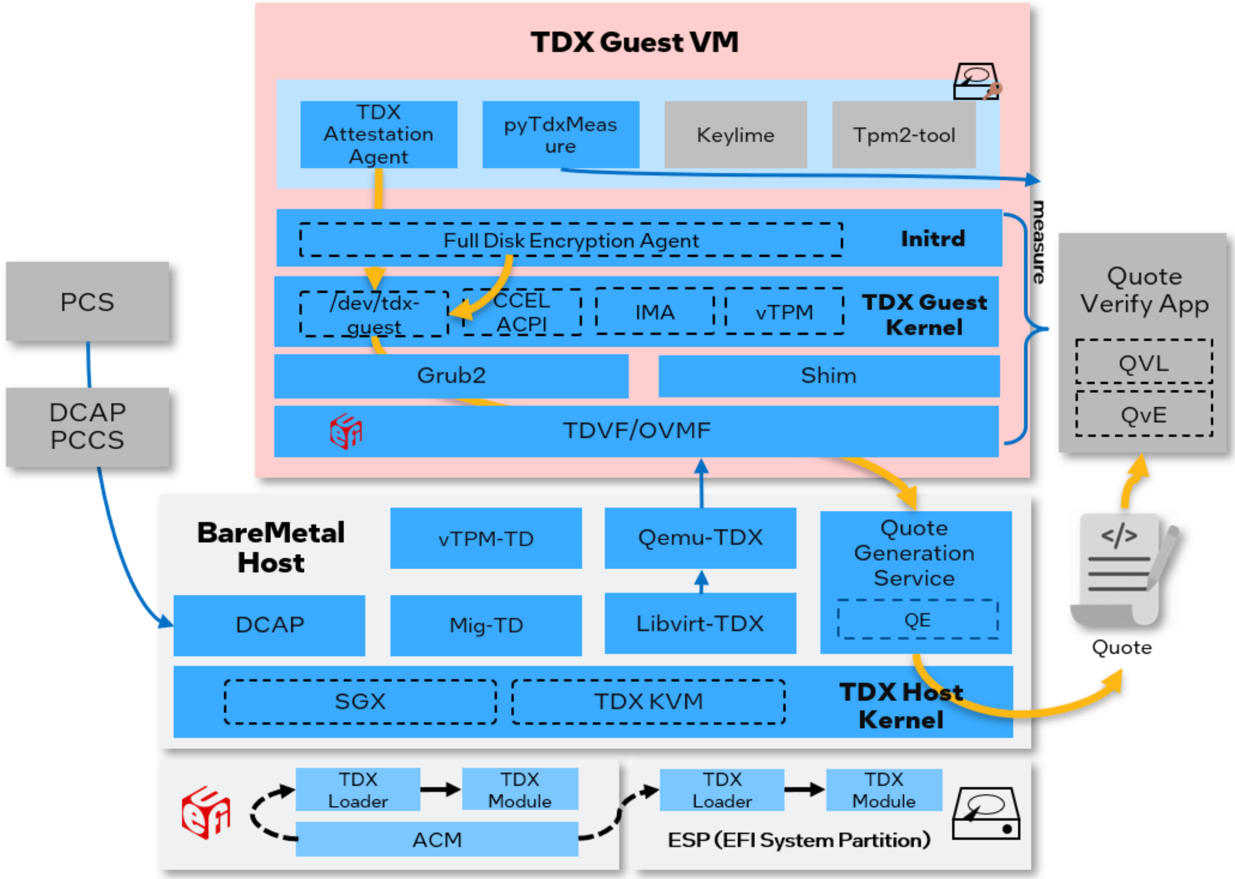


Figure 3: Linux Stack for Intel TDX 1.5

The open-source code for Linux Stack for Intel TDX 1.5 can be found at:

https://github.com/intel/tdx-tools.

NOTE: tdx-tools has multiple release tags. Please make sure to use the correct release tag which matches the release version. The Release tag and kernel version mapping can be found on tdx-tools wiki.

This document introduces:

- The deployment, cloud stack test, and other common uses for those who want to validate confidential workloads or tune performance.
- The debug and development methods for those who want to integrate stack in their IaaS/PaaS framework.

This document also introduces update for TDX 1.5:

- BIOS configuration for TDX on Emerald Rapids.
- End-to-end attestation for TDX on Emerald Rapids.
- TD migration introduction and usage guide.
- TD preserving usage guide.
- vTPM stack introduction and usage guide.

The OS supported in the document are Ubuntu 22.04 and RHEL 8.7.

1.2 Terminology

Term	Description
ACM	Authenticated Code Module
CCEL	Virtual Firmware Confidential Computing Event Log Table
CFV	Configuration Firmware Volume
CMR	Convertible Memory Ranges
CPLD	Complex Programmable Logic Device
CRB	Customer Reference Board
DCAP	Data Center Attestation Primitives
DIMM	Dual In-line Memory Module
ECC	Error Correction Code memory
EMR	Emerald Rapids
ESP	EFI System Partition
FV	Firmware Volume
GPA	Guest Physical Address
GVA	Guest Virtual Address
HOB	Hand Off Block
HVC	Hypervisor Virtual Console
IFWI	Integrated Firmware Image
IBV	Independent BIOS Vendor
IMA	Linux Integrity Measurement Architecture
Intel SGX	Intel® Software Guard Extensions (Intel® SGX)
Intel TDX	Intel® Trust Domain Extension (Intel® TDX)
LIV server	Live server is used for attestation with production CPU SKUs
LUKS	Linux Unified Key Setup
MigTD	Migration TD is a service TD to assist TD migration
MOK	Machine Owner Key
MRTD	Measurement of Trust Domain Firmware
OVMF	Open-source Virtual Machine Firmware
PCR	Platform Configuration Register
PCS	Provisioning Certification Service
PCCS	Provisioning Certificate Caching Service
PK/KEK/DB	Platform Key/Key Exchange Key/Database Key
QGS	Quote Generation Service
QMP	QEMU Monitor Protocol

QVE	Quote Verification Enclave
QVL	Quote Verification Library
RTMR	Runtime Measurement Register
SBX server	Sandbox server is used for attestation with pre-production CPU SKUs
SEAM	Secure Arbitration Mode
SPR	Sapphire Rapids
SVN	Security Version Number
TCB	Trusted-Computing Base
TCG	Trusted Computing Group
TDVF	Trusted Domain Virtual Firmware
TDVM	A TD guest VM
TDX-CI	TDX Crypto Integrity
TDX-LI	TDX Logical Integrity
TEE	Trusted Execution Environment
VMM	Virtual Machine Monitor
VMX	Intel Virtual Machine Extensions
vTPM	Virtual Trusted Platform Module
vTPM-TD	A service TD providing TPM device to TD

1.3 Using This White Paper

This white paper consists of TDX knowledge and a set of instructions to show how to build, install and use the software stack. It is intended to provide instructions that are targeted to various personas who want to use Intel TDX. These personas are rough definition of individuals who might have different responsibilities in the overall confidential system.

The following personas have been defined:

- Hardware IT Administrator
- Host OS Administrator
- Virtual Machine Administrator

The overall workflow of the white paper is illustrated in below diagram.

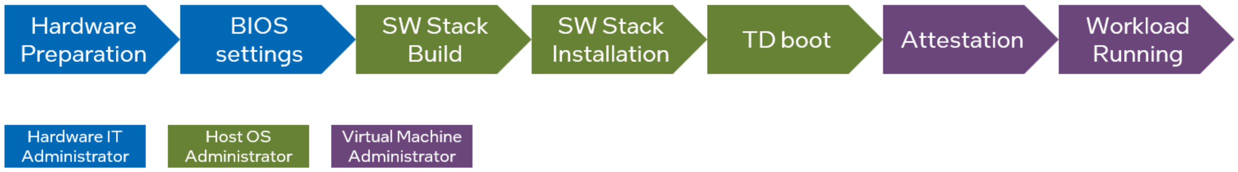


Figure 4: Overall workflow

You can read the entire documentation or jump directly to the section that most accurately describes your persona use case. This guide is organized in a linear manner, so reading all sections in order will make logical sense to a developer who considers themselves all the above personas.

- For hardware IT administrators, please start with chapter 2.
- For host OS administrators, please check chapter 3 – 9.
  - Chapter 3: TDX stack installation and basic validation
  - Chapter 4: TDX remote attestation
  - Chapter 5-9: TDX advanced features and solutions
- For virtual machine administrators, please start with chapter 10.

1.4 Document Structure

In this white paper, for code section, a line starting with "$ #" is a comment explaining the purpose of a command. A line starting with "$" is a command for users to perform. If there is no prefix, that is an output from a command.

```
$ # This is a comment of below command
$ This is a command to execute
This is the output of above command
```

2 Hardware and BIOS

2.1 Hardware

Linux Stacks for Intel TDX needs the following hardware support that enables Intel TDX:

- CPU Processor SKU. Contact Intel sales representative for details.
- Board configurations via hardware jumper or CPLD (complex programmable logic device). Contact your ODM/OEM vendor.
- DDR5 DIMM with the type of 10 × 4 ECC (error correction code memory)
- DDR5 RDIMMs with integrity protection.
- DIMM (Dual in-line memory module) population: It is recommended that all channel 0 slots have at least 1 DIMM populated. There are a total of 8 DIMMs per socket. The DIMM population must be symmetric across the integrated memory controllers.

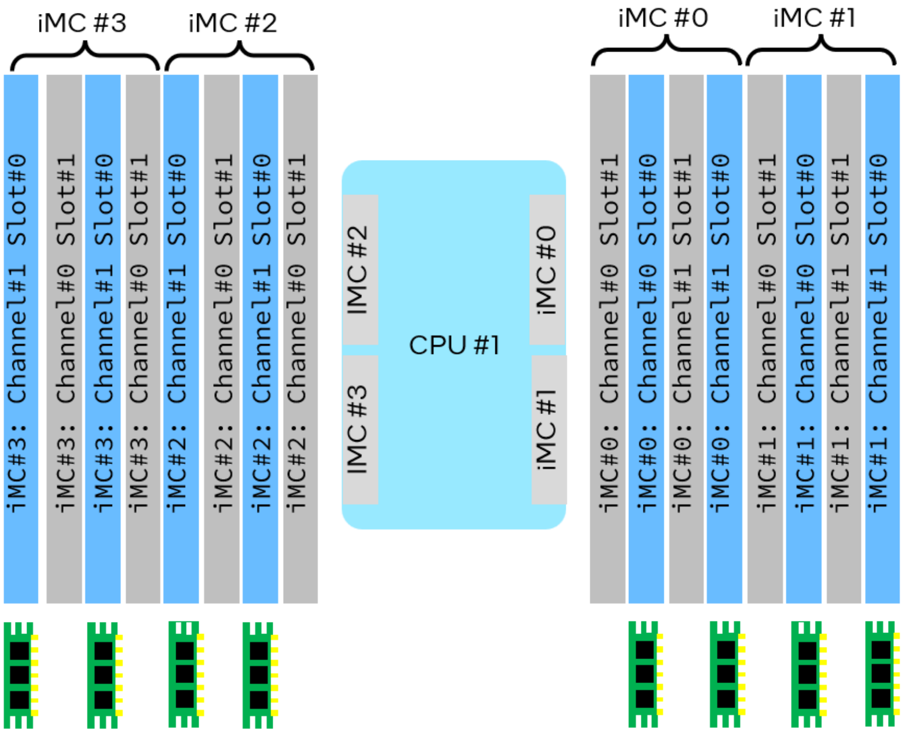


Figure 5: 8+0 DIMM Population for Intel TDX

Intel TDX also supports the full DIMM population 16+0 as follows:

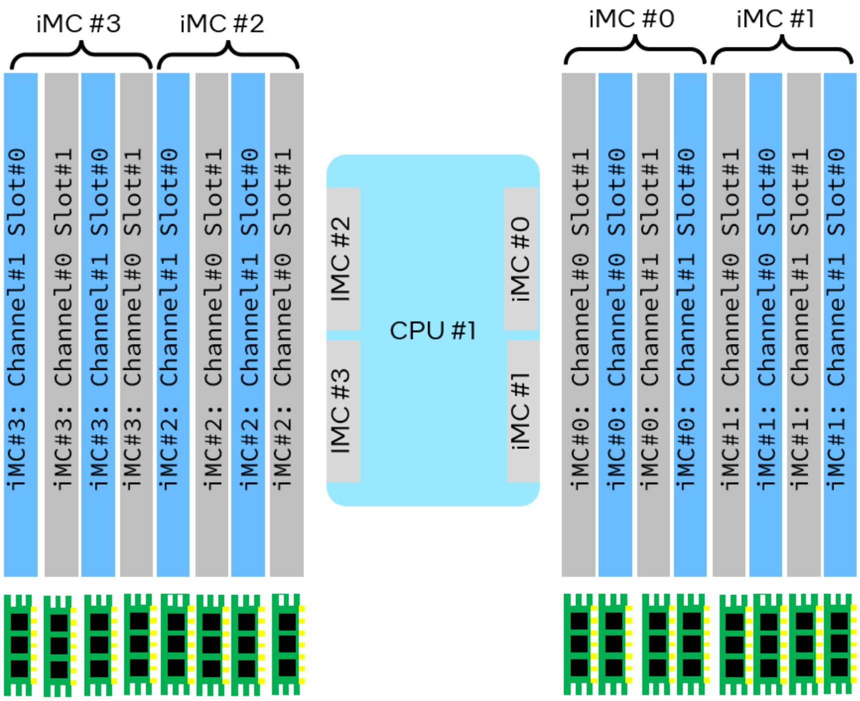
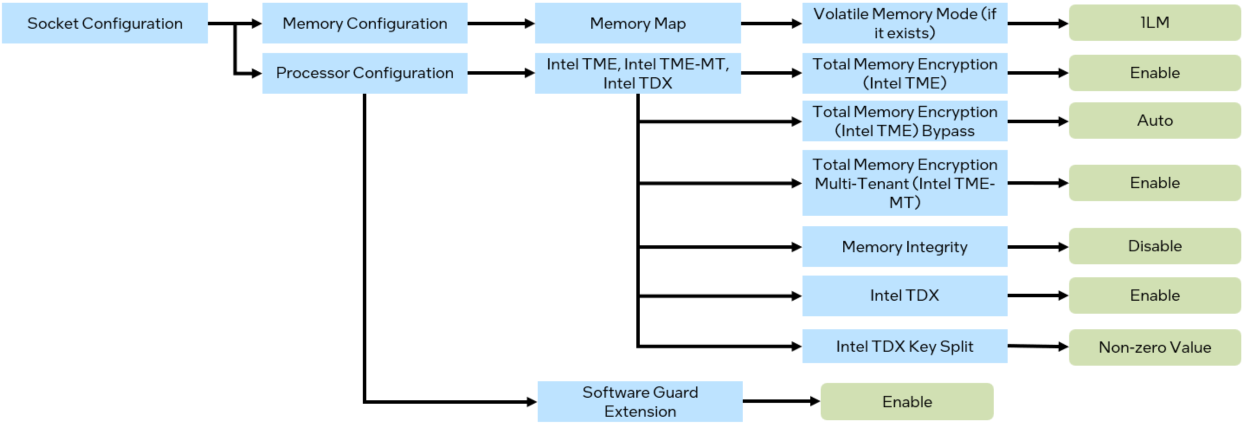


Figure 6: 16+0 DIMM Population for Intel TDX

2.2 BIOS

BIOS configurations are needed to support Intel TDX. Contact your Intel sales representative or IBV (independent BIOS vendor) for details. The following settings are examples for reference:


Socket Configuration → Memory Configuration → Memory Map → Volatile Memory Mode (if it exists) → 1LM

Socket Configuration → Processor Configuration → Intel TME, Intel TME-MT, Intel TDX → Total Memory Encryption (Intel TME) → Enable

Total Memory Encryption (Intel TME) Bypass → Auto

Total Memory Encryption Multi-Tenant (Intel TME-MT) → Enable

Memory Integrity → Disable

Intel TDX → Enable

Intel TDX Key Split → Non-zero Value

Processor Configuration → Software Guard Extension → Enable

Figure 7: BIOS settings for Intel TDX 1.0 on SPR

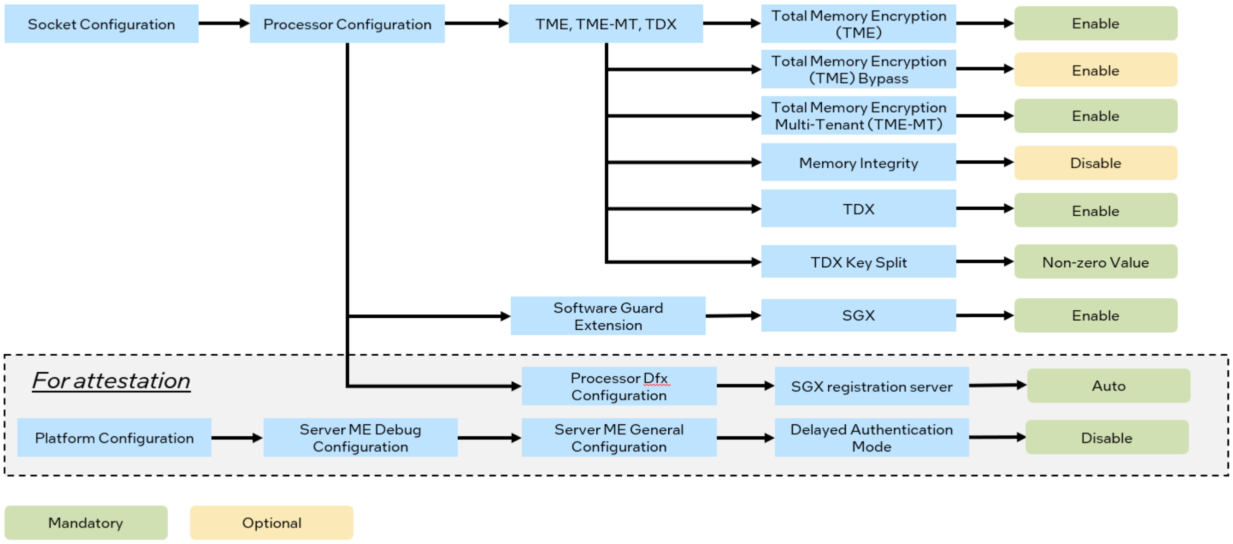


Figure 8: BIOS settings for Intel TDX 1.5 on EMR

Table 1: Intel TDX BIOS Configurations

BIOS Setting	Notes
Volatile Memory = 1LM	Intel TDX and CMR (Convertible Memory Ranges) logical integrity, isolation, and cryptographic integrity are only available with directly attached DDR5 memory. *NOTE: Please skip this setting if it doesn't exist in BIOS menu.*
Total Memory Encryption (Intel TME) = Enable	Intel TDX technology depends on Intel® Total Memory Encryption (Intel® TME).
Total Memory Encryption (Intel TME) Bypass = Auto	4th generation Intel Xeon Scalable processors introduce an Intel TME bypass mode to allow memory outside of Intel TME multi-tenant virtual machines, Intel SGX enclaves, and Intel TDX trust domains to be unencrypted to improve the performance of nonconfidential software.
Total Memory Encryption Multi-Tenant (TME-MT) = Enable	128 Intel TME – Multi-Tenant encryption keys.
Memory Integrity = *Disable*	4th generation Intel Xeon Scalable processor E-stepping does not support Intel TDX-CI, but only supports Intel TDX-LI.
Intel TDX = Enable	Intel TDX should be enabled.
TDX Key Split = <Non-zero Value)	Keys split between Intel TME multi-tenant and Intel TDX.
Software Guard Extension = *Enable*	Intel TDX depends on Intel SGX technology for hardware TCB and remote attestation.

Note: The configuration or the menus might be different on your BIOS. Contact the IBV or OEM/ODM for the correct settings.

3 Build and Installation

In this chapter, it assumes that the hardware and BIOS settings are ready for Intel TDX. It will introduce works for host OS administrators - how to build both host and guest packages, how to install the packages, how to create guest image for TD boot and how to validate end-to-end scenarios using Intel TDX tests.

3.1 Components

Linux Stack for Intel TDX is a vertical end-to-end stack including a series of components which are listed in Table 2: Linux Stack for Intel TDX Components.

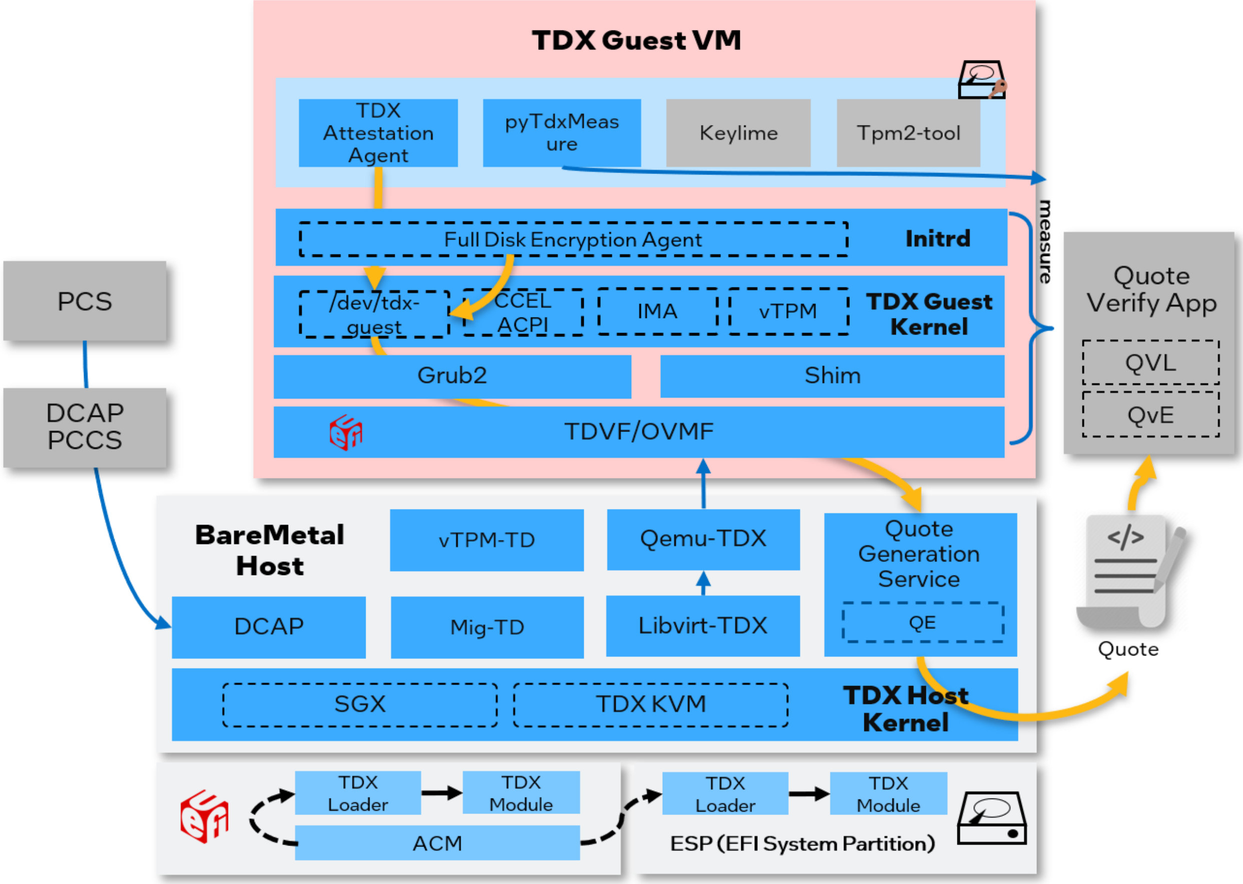


Figure 9: Linux Stack for Intel TDX 1.5 overview

There are multiple components in the Linux stack for both the host and guest.

Table 2: Linux Stack for Intel TDX Components

Components	Description	Source
Intel TDX Module	An attested software module running in SEAM Root Mode.	Intel Trust Domain Extensions
TDX Loader	A SEAM module intended to install an Intel TDX module into SEAM range.	Intel Trust Domain Extensions
Intel TDX Host Kernel	The host kernel with Intel TDX patches being upstreamed.	https://github.com/intel/tdx/tree/kvm
Intel TDX QEMU	QEMU with Intel TDX patches being upstreamed.	https://github.com/intel/qemu-tdx
Intel TDX Libvirt	Libvirt with Intel TDX patches being upstreamed.	https://github.com/intel/libvirt-tdx/tree/for_qemu_upstream
TDVF	Virtual firmware (aka OVMF) with Intel TDX features already upstreamed.	https://github.com/tianocore/edk2
TDVF-vTPM	Virtual firmware (aka OVMF) for vTPM.	https://github.com/tianocore/edk2
vTPM TD	A service TD providing TPM service to TD.	https://github.com/intel/vtpm-td
Migration TD	A service TD assisting TD live migration.	https://github.com/intel/MigTD
DCAP	Intel SGX-based DCAP (data center attestation primitives) for the platform certificate after registration.	https://github.com/intel/SGXDataCenterAttestationPrimitives
QGS	QGS provides the functionality of Intel TDX quote generation within an Intel SGX-based quote enclave. It is part of the DCAP running on the IaaS host or legacy VM.	https://github.com/intel/SGXDataCenterAttestationPrimitives
Intel TDX Guest Kernel	The guest kernel with Intel TDX patches being upstreamed.	https://github.com/intel/tdx/tree/guest-upstream
Grub2	The bootloader grub2 with Intel TDX patches already upstreamed.	https://github.com/intel/grub-tdx/tree/2.06-upstream-v4
Shim	The bootloader shim with Intel TDX patches already upstreamed.	https://github.com/intel/shim-tdx
Intel TDX Attestation Agent	A sample Intel TDX attestation agent to call	https://github.com/intel/SGXDataCenterAttestationPrimitives

	TDVMCALL.getQuote(). It is part of DCAP.	
PyTdxAttest	A Python measurement library that dumps RTMR, the CCEL ACPI table, and verifies the RTMR via replaying the TD event log.	https://github.com/intel/tdx-tools

NOTE:

1. *Some of the components have completed patch upstreaming such as Grub, Shim, and TDVF, while others are still in progress.*
2. *TDVF-vTPM, vTPM-TD, Migration TD are new components of the Linux Stack for Intel TDX 1.5.*

3.2 Building Stacks

For end-to-end stack setup and validation, tdx-tools provides downstream patches and a build tool to construct the whole stack in just a few simple steps.

The supported distros' versions are as follows for both host and guest packages:

- RHEL 8.x (Latest Version)
- Ubuntu 22.04

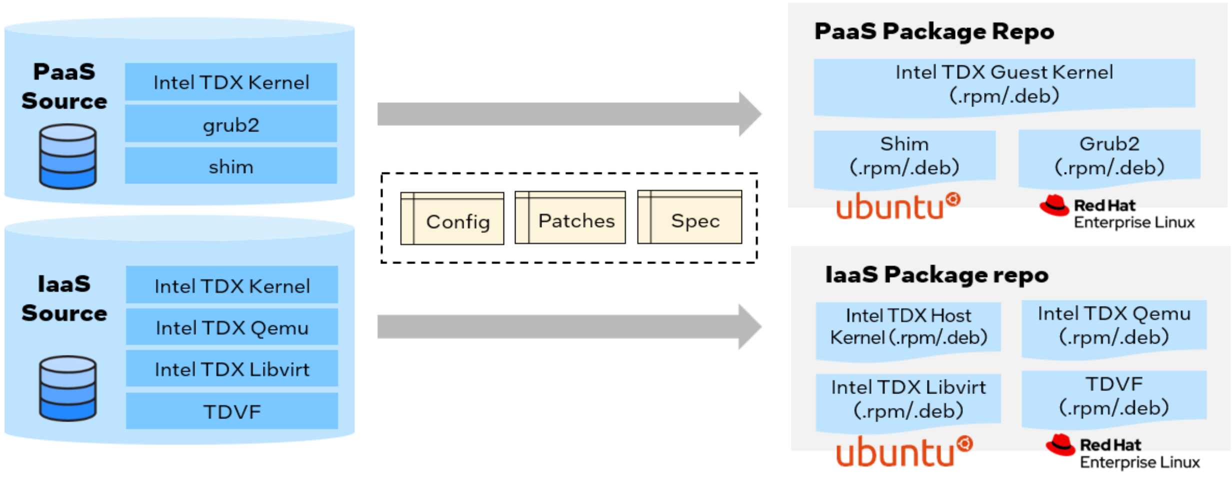


Figure 10: End-to-End Host and Guest Stack for Linux and Intel TDX

The end-to-end stack building includes two steps on any Linux development machine:

- Step 1: Build packages
- Step 2: Create guest image

3.2.1 Build Packages

A `build.sh` script is provided by tdx-tools to download the upstream source, apply Intel TDX patches from the directory `<build>/common`, and do package building.

Note: When obtaining tdx-tools, please make sure to use the correct tag which matches the release version.

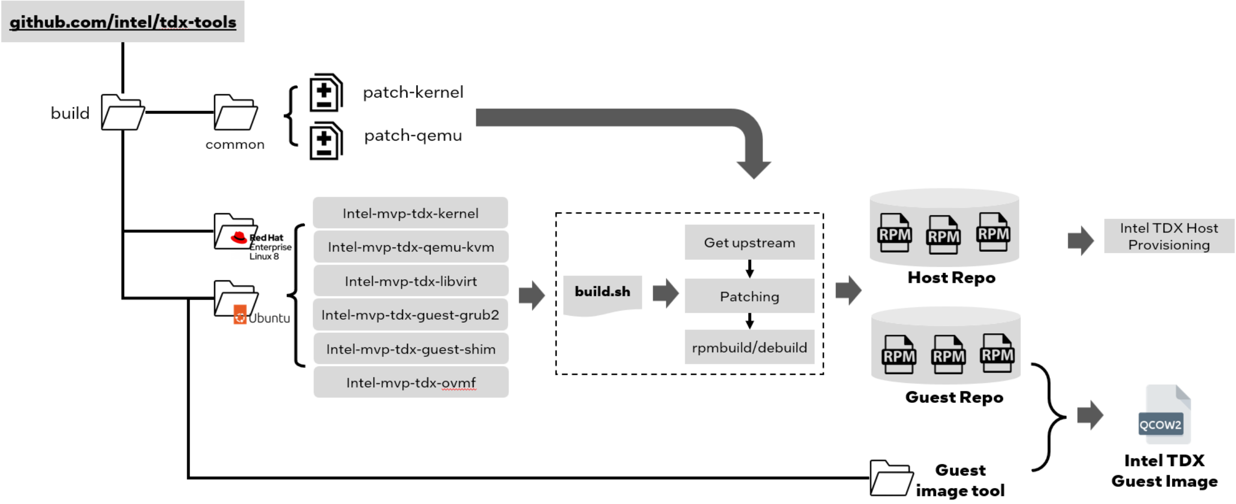


Figure 11: Build process for Intel TDX packages

The kernel config is provided in the kernel package directory with Intel TDX configurations. For example, RHEL-8 will use the path `build/rhel-8/intel-mvp-tdx-kernel/tdx-kernel.spec`. All kernel configurations have been optimized for TDX performance.

Below is an example using Ubuntu 22.04 to build the entire repo with all the packages using `./pkg-builder build-repo.sh`, but you will need to setup docker first, please see steps as below.

NOTE: The building process may take more than 1 hour or longer depending on the resource of building server.

```
$ # Follow https://docs.docker.com/engine/install/ to setup Docker.
$ # Add current user into docker group
$ sudo usermod -G docker -a $USER
$ # Restart docker service
$ sudo systemctl restart docker
$ # Make sure you get the correct tag. Here is an example of getting 2023ww27 tag
$ git clone git@github.com:intel/tdx-tools.git --branch 2023ww27

$ cd build/ubuntu-22.04/
$
$ # Build the all packages via build-repo.sh, and running it within pkg-builder
$ # container to avoid any issues of build environment
$ ./pkg-builder build-repo.sh
```

Below is an example of how to build individual packages on Ubuntu 22.04.

```
$ # If want to build individual package like intel-mvp-tdx-kernel
$ ./pkg-builder intel-mvp-tdx-kernel/build.sh
```

After the packages have been built successfully, two repositories are generated.

1. `build/ubuntu-22.04/host_repo`: includes the Intel TDX host kernel, Intel TDX QEMU, Intel TDX Libvirt, and TDVF.
2. `build/ubuntu-22.04/guest_repo` : includes the Intel TDX guest kernel, grub2, and shim.

3.2.2 Create Guest Image

The Intel TDX virtual machine requires guest images to be booted with a Intel TDX guest kernel, Intel TDX grub2 and shim packages for both grub boot and secure boot.

The image creation process is a little different for the different distros:

NOTE: The building process may take more than 1 hour or longer depending on the resource of building server.

- RHEL 8.x
  The default distro cloud image does not support an EFI schema. The tdx-tools repository provides `<tdx-tools>/build/rhel-8/guest-image/create-efi-img.sh` to create a RHEL EFI guest image via the kickstart[1] tool. Before running the script, please download official ISO image and change its name to match the one in `create-efi-img.sh`.

  Use `tdx-guest-stack.sh` to install the Intel TDX guest packages into the image using the following workflow.

[1] https://linuxhint.com/beginners-kickstart/

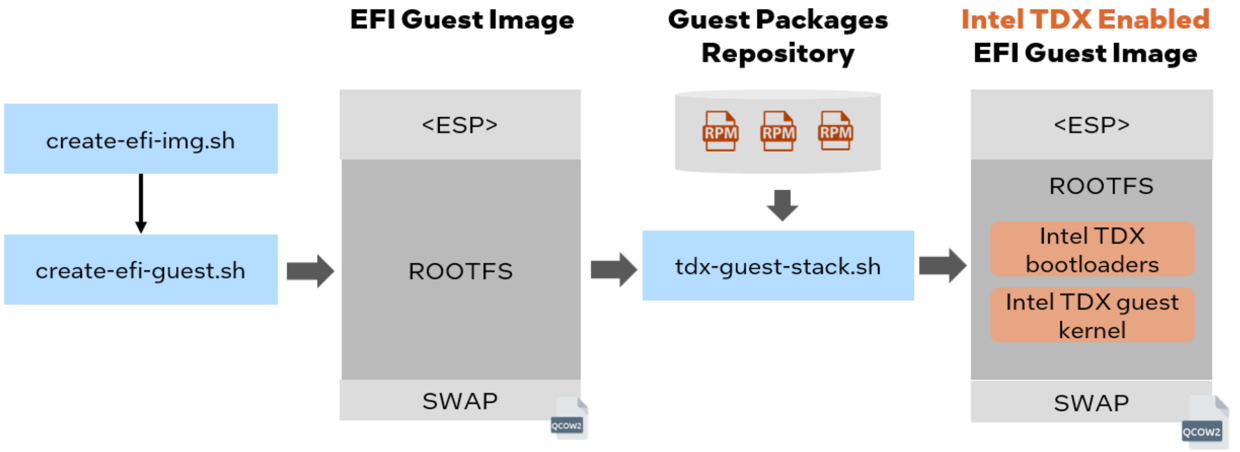


Figure 12: Create Intel TDX RHEL guest image

- Ubuntu 22.04

  Ubuntu provides EFI enabled guest/cloud images at https://cloud-images.ubuntu.com/. Use `<tdx-tools>/build/ubuntu-22.04/guest-image/create-ubuntu-image.sh` as follows:

```
$ # Prerequisite: build the Ubuntu packages via build-repo.sh
$
$ cd build/ubuntu-22.04/guest-image
$
$ # Install additional packages into guest image
$ ./create-ubuntu-image.sh
```

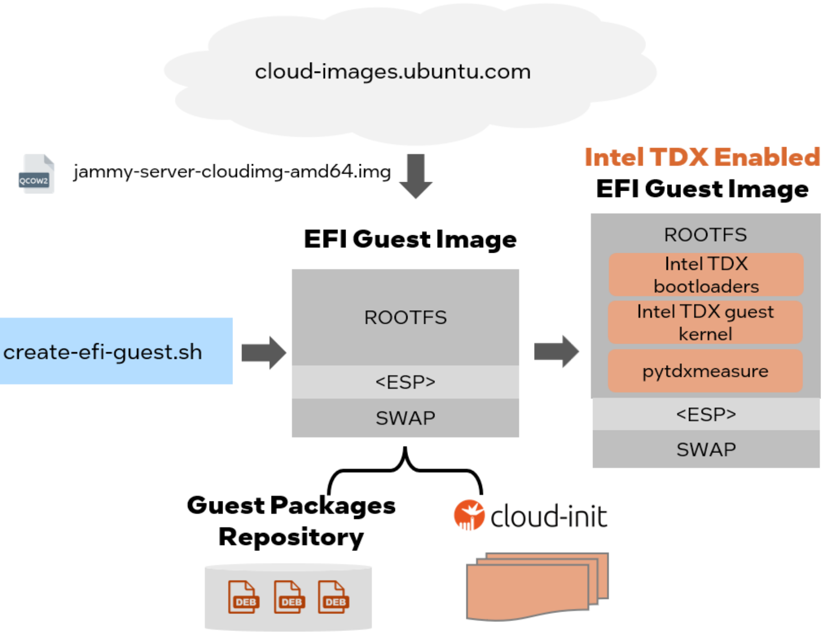


Figure 13: Create Intel TDX Ubuntu Guest Image

NOTE: The guest image can be further customized at tdx-tools/build/ubuntu22.04/guest-image:

```
Usage: create-ubuntu-image.sh [OPTION]...
  -h                          Show this help
  -c                          Create customize image (not from Ubuntu official cloud
image)
  -f                          Force to recreate the output image
  -n                          Guest host name, default is "tdx-guest"
  -u                          Guest user name, default is "tdx"
  -p                          Guest password, default is "123456"
  -s                          Specify the size of guest image
  -o <output file>            Specify the output file, default is tdx-guest-ubuntu-
22.04.qcow2.
                              Please make sure the suffix is qcow2. Due to
permission consideration,
                              the output file will be put into /tmp/<output file>.
  -r <guest repo>             Specify the directory including guest packages,
generated by build-repo.sh
```

3.3 Install IaaS Host

Perform the following steps to deploy the packages on IaaS host.

NOTE: If it's the first-time installing Intel TDX SW stack, please make sure Intel TDX is disabled in the BIOS before installing the SW packages. Once the Intel TDX packages have been installed, set the Intel TDX kernel as the default in grub, reboot, and enable Intel TDX in the BIOS.

If it's the first time installing the stack on a host, the overall steps of installing IaaS host will be like:

1. Disable Intel TDX in BIOS.
2. Install packages on the host.
3. Set the installed TDX kernel as default kernel.
4. Reboot and enable Intel TDX in BIOS.

3.3.1 Install Packages Manually

For RHEL 8.x host

- Move the generated host repo to a directory that will be used in the repo file.

```
$ sudo mkdir -p /srv/
$
$ # Build the RPM packages via above steps, the RPM package will be generated
$ # in <tdx-tools>/build/rhel-8/host_repo/

$ # Download TDX module packages and decompresse it to build/rhel-8/host-repo/
$ # Re-generate repo
$ tar -xf tdx-module.tar.gz -C build/rhel-8/host_repo/x86_64
$ createrepo_c build/rhel-8/host_repo/

$ # move the repo to /srv/tdx-host for later usage
$ sudo mv build/rhel-8/host_repo/ /srv/tdx-host
```

- Set up the host repository. Generate the file /etc/yum.repos.d/tdx-host-local.repo and add the following content.

```
$ cat /etc/yum.repos.d/tdx-host-local.repo
[tdx-host-local]
name=tdx-host-local
baseurl=file:///srv/tdx-host
enabled=1
gpgcheck=0
module_hotfixes=true
```

- Add the EPEL repo. It provides the packages of `capstone` and `libcapstone` required by Intel TDX QEMU.

```
$ sudo dnf install https://dl.fedoraproject.org/pub/epel/epel-release-latest-
8.noarch.rpm
```

- Install the host packages.

```
$ sudo dnf install intel-mvp-tdx-kernel intel-mvp-tdx-QEMU-kvm intel-mvp-ovmf
intel-mvp-tdx-libvirt intel-mvp-tdx-module-production
```

- If you get an error about qemu-kvm conflicts, remove the existing qemu-kvm package with the following command, and then re-run the command above to install host packages.

```
$ sudo dnf remove qemu-kvm
```

- Add `numa_balancing=disable` into grub menu.

```
$ vi /etc/default/grub

# Add "numa_balancing=disable" in GRUB_CMDLINE_LINUX
GRUB_CMDLINE_LINUX=". . . numa_balancing=disable"

$ sudo grub2-mkconfig -o /boot/efi/EFI/redhat/grub.cfg
```

- Set TDX kernel as default kernel.

```
$ vi /etc/default/grub

# Add "numa_balancing=disable" in GRUB_CMDLINE_LINUX_DEFAULT
GRUB_CMDLINE_LINUX_DEFAULT=". . . numa_balancing=disable"

$ sudo update-grub
```

For Ubuntu 22.04 host

- Install all Debian packages.

```
$ # Build the DEB packages via the above steps, the DEB packages will be generated
$ # to <tdx-tools>/build/ubuntu-22.04/host_repo/
$ cd host_repo
$ sudo apt -y --allow-downgrades install ./*.deb
```

- Add `numa_balancing=disable` into grub menu.

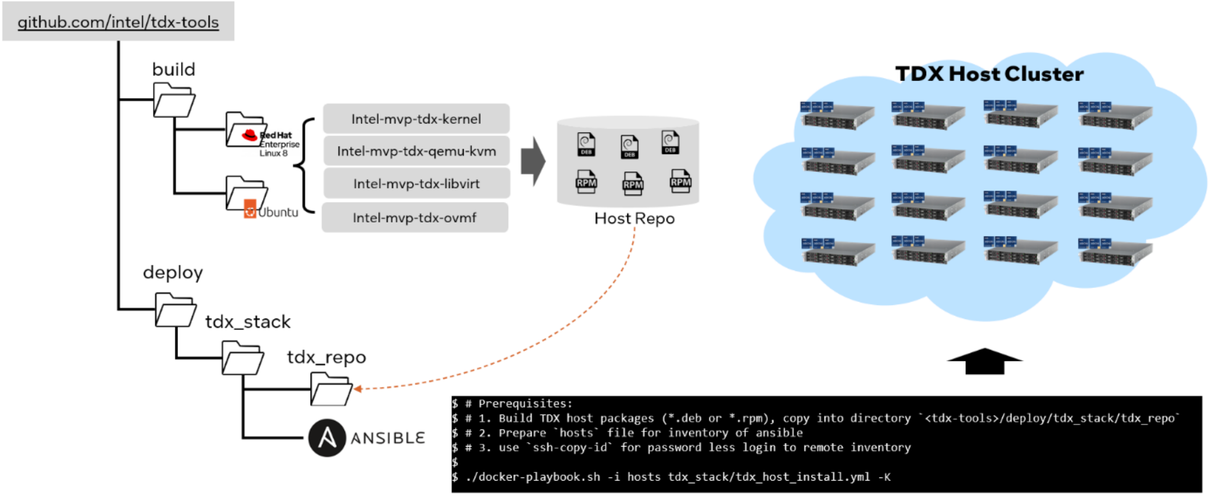
```
$ vi /etc/default/grub

# Add "numa_balancing=disable" in GRUB_CMDLINE_LINUX_DEFAULT
GRUB_CMDLINE_LINUX_DEFAULT=". . . numa_balancing=disable"

$ sudo update-grub
```

- Set TDX kernel as default kernel.

```
$ grep -A100 submenu /boot/grub/grub.cfg | grep menuentry | grep <TDX kernel
version>

$ # Use the string in above output, such as "gnulinux-6.2.0-mvp4v1+2-
$ # generic-advanced-34db9317-bf73-44c3-8425-2fa83446e8d5" in
$ # /etc/default/grub file as value of “GRUB_DEFAULT"

$ vi /etc/default/grub
GRUB_DEFAULT="gnulinux-6.2.0-mvp4v1+2-generic-advanced-34db9317-bf73-44c3-8425-
2fa83446e8d5"

$ sudo update-grub
```

3.3.2 Deploy via Ansible

Use the ansible based “TDX Deployment Tool” to deploy the host stack to multiple server nodes or guest stack to multiple TD VMs.



```
$ # Prerequisites:
$ # 1. Build TDX host packages (*.deb or *.rpm), copy into directory `<tdx-tools>/deploy/tdx_stack/tdx_repo`
$ # 2. Prepare `hosts` file for inventory of ansible
$ # 3. use `ssh-copy-id` for password less login to remote inventory
$
$ ./docker-playbook.sh -i hosts tdx_stack/tdx_host_install.yml -K
```

Figure 14: Deploy TDX host stack via Ansible

NOTE: Current Ansible script only support deployment on Ubuntu 22.04.

Before using the script there are a couple pre-requisites.

1. Build the host *.deb repositories. Refer to section 3.2.1 Build Packages. The final built files will be at `<tdx-tools>/build/ubuntu-22.04/host_repo`.
2. Copy all *.deb packages to `<tdx-tools>/deploy/tdx_stack/tdx_repo/`

```
$ cp build/ubuntu-22.04/host_repo/*.deb deploy/tdx_stack/tdx_repo/
```

3. Prepare ansible inventory host file and enable password-less login on all managed nodes, please refer to this tutorial.

```
$ # The content of an example inventory file
$ cat deploy/tdx_stack/hosts
tdx@10.0.0.2
tdx@10.0.0.3
tdx@10.0.0.4

$ # Enable the SSH password less login
$
$ ssh-copy-id tdx@10.0.0.2
...
$ ssh-copy-id tdx@10.0.0.3
...
$ ssh-copy-id tdx@10.0.0.4
```

4. Setup ansible docker to create the build image.

```
$ ./docker-playbook.sh rebuild
```

5. Run playbook in docker for auto deployment process on all managed nodes

3.3.3 Reboot with the Intel TDX kernel

After installing the Intel TDX kernel and host packages successfully, reboot the system into the BIOS menu and enable Intel TDX. Refer to Section 2.2 on the BIOS settings. To verify that Intel TDX is enabled use the script check-tdx-host.sh after the system is booted. Alternatively, the below steps can also be used to determine that Intel TDX has been successfully enabled.

- Check whether TDX Module is initialized. The expected output is "TDX module initialized".

```
$ sudo dmesg | grep -i tdx
...
tdx: TDX module initialized.
```

- Check Intel TME enable status, expecting a return code of 1.

```
$ sudo rdmsr -f 1:1 0x982
1
```

- Check Intel TME max keys.

```
$ sudo rdmsr -f 50:36 0x981
```

- Check the Intel SGX and MCHECK status, expecting a code of 0.

```
$ sudo rdmsr 0xa0
0
```

- Check the Intel TDX Status, expecting a code of 1.

```
$ sudo rdmsr -f 11:11 0x1401
1
```

NOTE: All the above checking steps should be successful with expected result returned before moving forward to the next steps.

- Check the number of Intel TDX keys.

```
$ sudo rdmsr -f 63:32 0x87
1
```

- Check the information for the Intel TDX module.

```
$ cat /sys/firmware/tdx/tdx_module/*
```

3.4 Manage the TD

Like a normal virtual machine, a TD guest can be launched by QEMU via command line or orchestrated by Libvirt via XML templates. This chapter introduces how to manage the lifecycle of a TD guest for diverse boots such as secure boot, direct boot, and grub boot.

NOTE: Please make sure to use the correct tag of tdx-tools which matches the release version.

3.4.1 Overview

You can boot a TD guest either by using the QEMU command line or by using a Libvirt XML template and virsh commands. Libvirt translates the XML template to QEMU commands and calls QEMU-kvm to complete the VM boot. Similarly, you can call QEMU-kvm directly with parameters to boot a VM.

The following diagram illustrates the TD guest boot type and boot process.

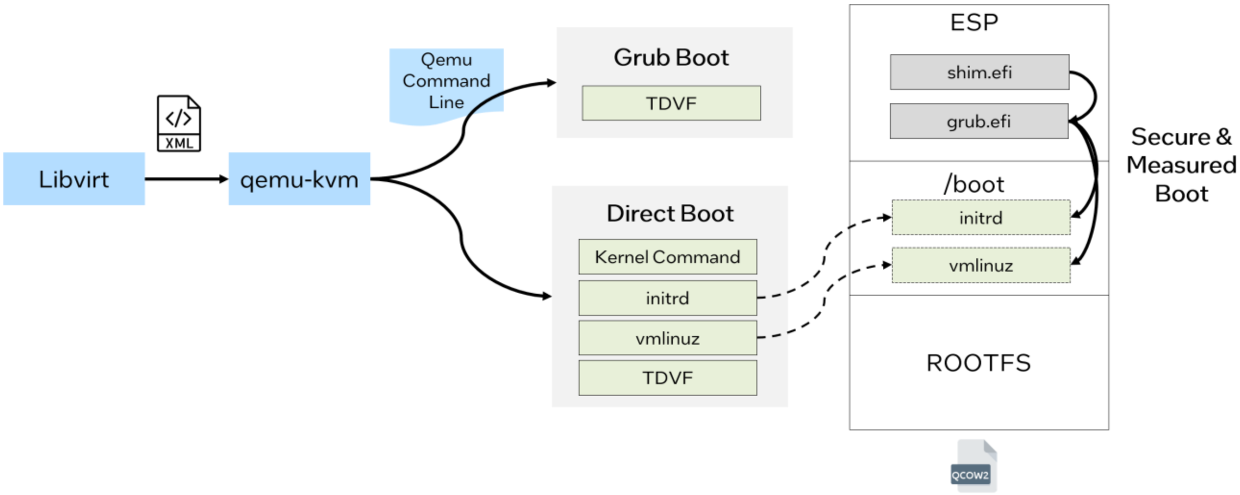


Figure 15: TD Guest Boot Process

The following table explains the different boot types:

Table 3: Boot Types for TD Guest

Boot Type	Description	Difference from a non-confidential VM
Direct Boot	Boot the guest by explicitly specifying a kernel binary via the QEMU launching parameter "-kernel", by specifying the initrd binary via QEMU launching parameter "-initrd", and by specifying the kernel command via the QEMU launching parameter "-append". Bootloaders such as shim/grub are not involved in direct boot.	No differences on QEMU launch parameters for confidential VM, but requires TDVF/OVMF to do measured boot and record the measurement into the RTMR (Runtime Measurement Register) register
Grub Boot	Boot the guest without "-kernel" and "-append" in QEMU launching params. The OVMF/TDVF searches for and starts the bootloader from the ESP.	No differences on QEMU launch parameters for confidential VM, but requires Intel TDX Grub2 to do measured boot and record the measurement into RTMR register
Measured Boot	It is the process of measuring and storing securely (i.e. using a TPM) the next stage object in the boot process by the UEFI BIOS, bootloader, kernel, etc.	The secure register is a PCR register in a trusted computing group (TCG)-defined trusted platform module (TPM) while it is the RTMR in a Intel TDX module
Secure Boot	Secure boot is a security standard developed by members of the PC industry to ensure that a device is booted using only software that is trusted by the original equipment manufacturer (OEM). The Secure boot certificate should be protected by measured boot.	The secure boot certificate can be enrolled in the runtime of a guest VM for non-confidential VM's. However, the secure boot must be enrolled in the TDVF offline for the consistent measurement on MRTD (measurement of trust domain)

The detailed boot flow for different TD boot methods can be found in Figure 1614: Detailed boot flow for different TD boot

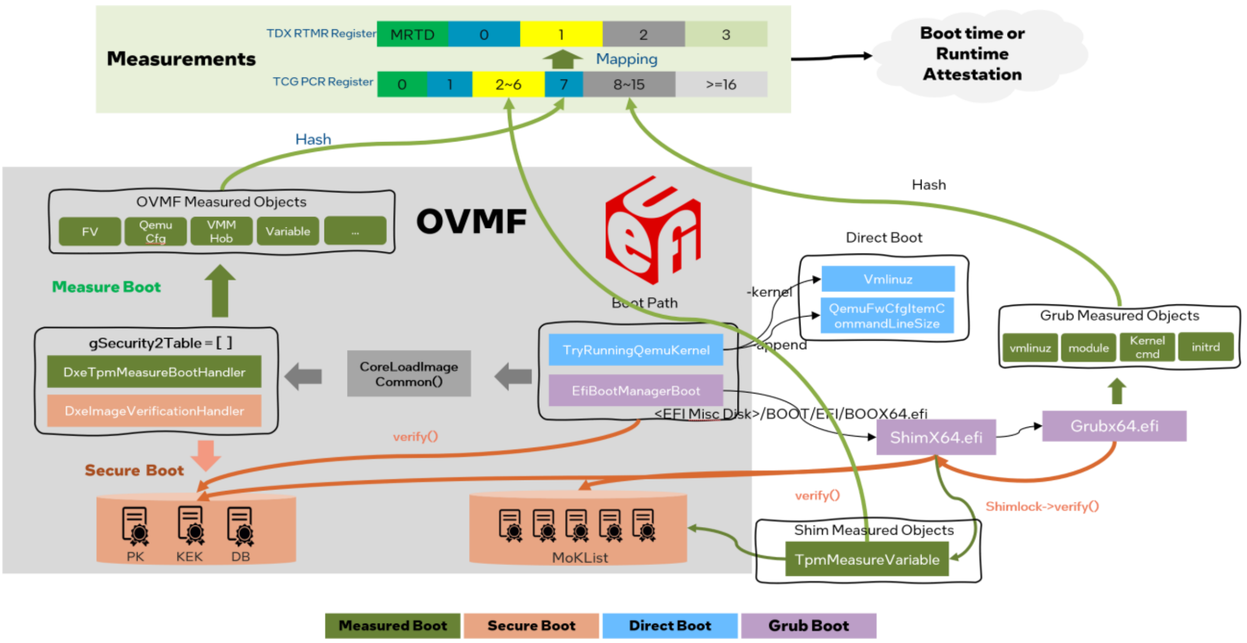


Figure 16: Detailed boot flow for different TD boot

In Figure 1614: Detailed boot flow for different TD boot:

Measured Boot

1. In OVMF, the image handler `DxeTpmMeasureBootHandler` will be triggered when loading EFI image via `CoreLoadImageCommon()`.
2. In OVMF, `DxeTpmMeasureBootHandler` will measure the objects like FV, QEMU CFG, VMM Hob, Variable into TCG PCR Register. In TD guest, the measurement will also be extended to RTMR register if vTPM does not exist.
3. In boot loader ShimX64.efi, `TpmMeasureVariable()` will measure the secure boot's certificates into TCG PCR or TDX RTMR register.
4. Boot loader GrubX64.efi measures kernel binary and cmdline, initrd binary and grub's module into TCG PCR or TDX RTMR register.

The mapping between TCG PCR register and RTMR is as below.

- PCR #1, #7 ⬄ RTMR #0
- PCR #2~#6 ⬄ RTMR #1
- PCR #8~#15 ⬄ RTMR #2

Secure Boot

1. In OVMF, the image handler `DxeImageVerificationHandler` will be triggered when loading EFI image via `CoreLoadImageCommon()`.

2. In OVMF, `DxeImageVerificationHandler` will use UEFI secure boot's DB key verify the certificate from each of load EFI image.
3. ShimX64.efi and GrubX64.efi will use UEFI secure boot's DB key or Linux secure boot's MoK (Machine Owner Key) to verify the certificate of kernel, kernel module etc.
4. All certificates, including UEFI secure boot and Linux secure boot, are measured into TDX RTMR register.

Direct Boot

1. In direct boot path, the kernel binary is started and measured by `TryRunningQEMUKernel()`.
2. In direct boot path, the kernel command and initrd are measured by the EFI stub of Linux kernel

Refer to the measure log for direct boot for a sample of what the output should look like.

Grub Boot

1. In grub boot, ShimX64.efi will help bring the UEFI secure boot to Linux secure boot. Normally UEFI secure boot will use MSFT UEFI certificates[2]. But here it needs a new key to sign customized kernel/grub/shim, please refer to section 3.4.2.3 Secure Boot
2. In grub boot, GrubX64.efi will measure kernel binary/command and initrd binary.

Refer the measure log for grub boot.

[2] https://learn.microsoft.com/en-us/windows-hardware/manufacture/desktop/windows-secure-boot-key-creation-and-management-guidance?view=windows-11

3.4.2 Boot TD Guest

3.4.2.1 Launch via QEMU

Since the QEMU parameter list is quite long and complicated, tdx-tools provides the start-qemu.sh script to handle some parameters by default. It supports both direct boot and grub boot of TD guest. It also provides a few interactive parameters to meet customization requirements.

Note: The parameters in `start-qemu.sh` *may vary along with different Intel TDX kernel and Intel TDX QEMU versions. Please make sure to use the correct tag of tdx-tools which matches the release.*

The `start-qemu.sh` script offers several parameters to boot TD guests on demand. The parameters are listed in Table 4: start-qemu.sh parameters:

Table 4: start-qemu.sh parameters

Parameter	Description
`-i <guest image file>`	Guest image file name and location
`-k <kernel file>`	Kernel binary name and location
`-t [legacy | efi | td]`	VM type supported; default is "td"
`-b [direct | grub]`	Boot type, default value is "direct" which requires kernel binary specified via "-k"
`-p <Monitor port>`	Monitor port via telnet. Refer to the usage of QEMU Monitor
`-f <SSH Forward port>`	Host port used for guest VM SSH forwarding. Refer to QEMU SSH port forwarding
`-o <OVMF file>`	BIOS firmware device file. OVMF/TDVF is used for "td" and "efi" VM type. "efi" is used for non-confidential VM, while "td" is used for TD VM guest
`-m <11:22:33:44:55:66>`	MAC address of VM. If MAC address changes for a TD guest, RTMR value will change and Intel TDX measurement will fail
`-q [tdvmcall | vsock]`	TD quote generation supports using tdvmcall or vsock. Choose the corresponding value to boot TD guest.
`-c <number>`	Number of vCPU. Default value is 1.
`-r <root partition>`	Root partition for direct boot, default is /dev/vda3
`-e <extra kernel command>`	Extra kernel command needed in VM boot
`-v`	Flag to enable vsock
`-d`	Flag to enable "debug=on" for GDB guest. Refer to chapter **Error! Reference source not found. Error! Reference source not found.**

-s	Flag to use serial console instead of hypervisor virtual console (HVC).
-h	Show usage help

- Direct boot TD guest via QEMU command

  This is an example of direct boot using start-qemu.sh. You need to provide the guest image and kernel image as shown. Direct boot is used by default, so it's not required to use “-b direct”.

```
$ ./start-qemu.sh -i <guest image> -k <kernel binary>
```

- Grub boot TD guest via QEMU command

  This is an example of grub boot using start-qemu.sh. You need to provide the guest image and specify to use grub boot via “-b grub”.

```
$ ./start-qemu.sh -i <guest image> -b grub
```

- Direct boot non-confidential guest via QEMU command

  This is an example of how to direct boot a non-TD guest. Provide the guest image and kernel image as shown. It requires using "-t efi" to boot non-confidential guest via OVMF/TDVF or "-t legacy" to boot non-confidential guest via legacy SeaBIOS.

```
$ ./start-qemu.sh -i <guest image> -k <kernel image> -t efi
$ ./start-qemu.sh -i <guest image> -k <kernel image> -t legacy
```

You can safely exit the TD console using “CTRL+]”.

3.4.2.2 Launch via Libvirt

Libvirt is a popular orchestrator to manage the VM guest via the virsh command. Tdx-tools provides both direct boot and grub boot XML templates for TD guest at tdx-tools/doc/.

Template	Description
tdx_libvirt_direct.xml.template	TD guest direct boot
tdx_libvirt_grub.xml.template	TD guest grub boot

NOTE: The templates may vary with a different kernel version or QEMU version. Please make sure to use the correct tag of tdx-tools which matches the release version.

To create the final VM's XML from the template, update the XML template to refer to the guest image, kernel image, and OVMF binary:

- Update OVMF binary path. It's usually at `/usr/share/qemu/OVMF.fd`

```
<loader>/path/to/OVMF.fd</loader>
```

- Update guest image

```
<source file="/path/to/guest-image.qcow2"/>
```

- Update kernel image (This is not needed when using grub boot template)

```
<kernel>/path/to/vmlinuz-jammy</kernel>
```

Unlike QEMU, Libvirt uses the concept of a domain to manage the VM lifecycle across reboot cycle. Libvirt distinguishes between two different types of domains: transient and persistent[3].

- Transient domains only exist until the domain is shut down or when the host server is restarted.
- Persistent domains last indefinitely.

This example uses a Transient domain to start a TD guest:

```
$ virsh create tdx_libvirt_direct.xml
```

Check whether a TD guest is running with the following command. It's expected to see a TD guest running.

[3] https://wiki.libvirt.org/VM_lifecycle.html

```
$ virsh list
 Id    Name                                      State
--------------------------------------------------------------
 2     td-guest                                  running
```

Enter the TD guest console with the following command.

```
$ virsh console <TD guest name>
```

3.4.2.3 Secure Boot

Secure boot for a TD guest is almost the same as a traditional non-confidential VM. The major difference is the OMVF.fd/TDVF.fd needs to be measured into MRTD statically. Since the EFI variable is read-only in runtime with the TDX guest VM, it does not permit enrolling the secure boot key into the EFI variable FV (firmware volume) via a tool such as EnrollDefaultKey at runtime. Instead, a new tool called ovmfkeyenroll from tdx-tools was developed to help enroll the secure boot certificate offline before the measurement happens.

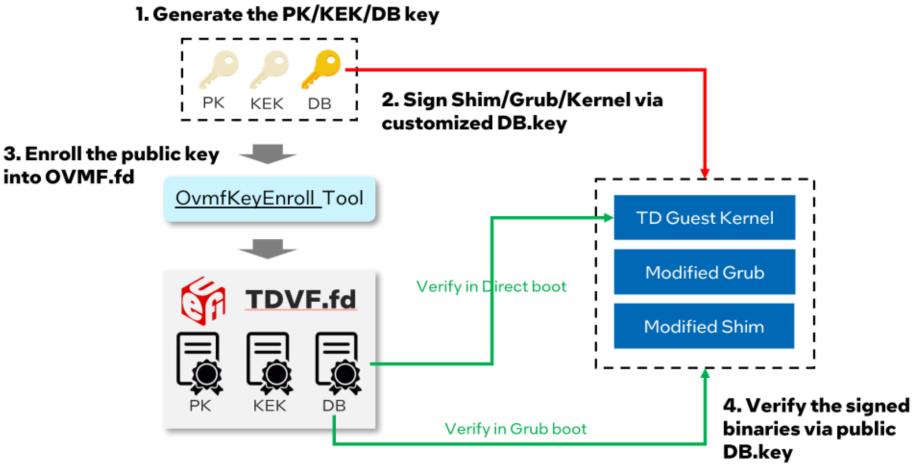

1. Generate the PK/KEK/DB key
PK
KEK
DB
2. Sign Shim/Grub/Kernel via customized DB.key
3. Enroll the public key into OVMF.fd
OvmfKeyEnroll Tool
TDVF.fd
PK
KEK
DB
Verify in Direct boot
TD Guest Kernel
Modified Grub
Modified Shim
Verify in Grub boot
4. Verify the signed binaries via public DB.key

Figure 17: Enable Secure Boot

The steps of enrolling the secure boot key are as follows:

- Step 1: Generate customized secure boot keys and certificates, instead of using a Microsoft certificate.

```
#!/bin/bash
NAME="Test"
openssl req -new -x509 -newkey rsa:2048 -subj "/CN=$NAME PK/" -keyout PK.key \
-out PK.crt -days 3650 -nodes -sha256
openssl req -new -x509 -newkey rsa:2048 -subj "/CN=$NAME KEK/" -keyout KEK.key \
-out KEK.crt -days 3650 -nodes -sha256
openssl req -new -x509 -newkey rsa:2048 -subj "/CN=$NAME DB/" -keyout DB.key \
-out DB.crt -days 3650 -nodes -sha256
openssl x509 -in PK.crt -out PK.cer -outform DER
openssl x509 -in KEK.crt -out KEK.cer -outform DER
openssl x509 -in DB.crt -out DB.cer -outform DER
chmod 0600 *.key

# Generate 3 UUID for the next step.
pk-key-guid=$(python3 -c 'import uuid; print(str(uuid.uuid1()))')
kek-guid=$(python3 -c 'import uuid; print(str(uuid.uuid1()))')
db-key-guid=$(python3 -c 'import uuid; print(str(uuid.uuid1()))')
```

Refer to the following to learn more about the different types of digital certificates.

- Managing EFI Boot Loaders for Linux: Controlling Secure Boot
- UEFI Specification

- Step 2: Build and install the ovmfkeyenroll tool from the following source.

```
$ python3 -m pip install ovmfkeyenroll
```

- Step 3: Enroll key into OVMF.fd (aka TDVF.fd)

```
$ ovmfkeyenroll -fd <absolute-path-to-OVMF.fd> \
                -pk <pk-key-guid> <absolute-path-to>/PK.cer \
                -kek <kek-guid> <absolute-path-to>/KEK.cer \
                -db <db-key-guid> <absolute-path-to>/DB.cer
```

NOTE: Replace <-guid> with the corresponding UUID generated above.*

- Step 4: Install signing tool
  - Option 1: Build from source: sbsigntools
  - Option 2: Use RPM or DEB packages built by a third-party.

```
$ wget https://download-
ib01.fedoraproject.org/pub/fedora/linux/releases/33/Everything/
x86_64/os/Packages/s/sbsigntools-0.9.4-2.fc33.x86_64.rpm
$ sudo rpm -ihvf sbsigntools-0.9.4-2.fc33.x86_64.rpm
```

- Step 5: Extract the following components from the guest's packages
  - shimx64.efi
  - mmx64.efi
  - grubx64.efi
  - fbx64.efi
  - guest kernel binary file like vmlinuz
- Step 6: Sign Shim/Grub/Kernel with customized secure boot key

```
$ sbsign --key <path-to>/DB.key --cert <path-to>/DB.crt --output shimx64-
signed.efi shimx64.efi
$ sbsign --key <path-to>/DB.key --cert <path-to>/DB.crt --output mmx64-signed.efi
mmx64.efi
$ sbsign --key <path-to>/DB.key --cert <path-to>/DB.crt --output grubx64-
signed.efi grubx64.efi
```

```
$ sbsign --key <path-to>/DB.key --cert <path-to>/DB.crt --output fbx64-signed.efi
fbx64.efi
$ sbsign --key <path-to>/DB.key --cert <path-to>/DB.crt --output vmlinuz-signed
vmlinuz-<guest-kernel-version>
```

NOTE: if the DB.key or DB.crt file to be signed is not in the same directory then a relative address needs to be used.

The following files are created:

  - shimx64-signed.efi
  - mmx64-signed.efi
  - grubx64-signed.efi
  - fbx64-signed.efi
  - vmlinuz-signed

- Step 7: Customize guest QCOW2 Image
  - Create the directories for mounting ESP and rootfs partitions:

```
$ mkdir -p workspace/efi
$ mkdir -p workspace/rootfs
```

  - Connect the QCOW2 image to `/dev/nbdx`:

```
$ sudo modprobe nbd max_part=8
$ sudo qemu-nbd --connect=/dev/nbd0 /path/of/td-guest.qcow2
```

  - Mount ESP and rootfs

    For RHEL 8.x:

```
$ sudo mount /dev/nbd0p2 workspace/efi
$ sudo mount /dev/nbd0p3 workspace/rootfs
```

For Ubuntu 22.04:

```
$ sudo mount /dev/nbd0p15 workspace/efi
$ sudo mount /dev/nbd0p1 workspace/rootfs
```

  - Replace the files

For RHEL 8.x:

```
$ sudo su
$ cp /path/to/shimx64-signed.efi workspace/efi/EFI/BOOT/BOOTX64.EFI
$ cp /path/to/shimx64-signed.efi workspace/efi/EFI/redhat/shimx64.efi
$ cp /path/to/fbx64-signed.efi workspace/efi/EFI/BOOT/fbx64.efi
$ cp /path/to/mmx64-signed.efi workspace/efi/EFI/BOOT/mmx64.efi
$ cp /path/to/mmx64-signed.efi workspace/efi/EFI/redhat/mmx64.efi
$ cp /path/to/grubx64-signed.efi workspace/efi/EFI/redhat/grubx64.efi

$ # please pay attention to replace the correct version of the kernel
$ cp /path/to/vmlinuz-signed workspace/rootfs/boot/vmlinuz-<kernel-version>
```

For Ubuntu 22.04:

```
$ sudo su
$ cp /path/to/shimx64-signed.efi workspace/efi/EFI/BOOT/BOOTX64.EFI
$ cp /path/to/shimx64-signed.efi workspace/efi/EFI/ubuntu/shimx64.efi
$ cp /path/to/fbx64-signed.efi workspace/efi/EFI/BOOT/fbx64.efi
$ cp /path/to/mmx64-signed.efi workspace/efi/EFI/BOOT/mmx64.efi
$ cp /path/to/mmx64-signed.efi workspace/efi/EFI/ubuntu/mmx64.efi
$ cp /path/to/grubx64-signed.efi workspace/efi/EFI/ubuntu/grubx64.efi
$
$ # please pay attention to replace the correct version of the kernel
$ cp /path/to/vmlinuz-signed workspace/rootfs/boot/vmlinuz-<kernel-version>
```

- Step 8: Unmount the ESP and rootfs partitions:

  For RHEL 8.x:

```
$ sudo mount /dev/nbd0p2 workspace/efi
$ sudo mount /dev/nbd0p3 workspace/rootfs
```

  For Ubuntu 22.04:

```
$ sudo mount /dev/nbd0p15 workspace/efi
$ sudo mount /dev/nbd0p1 workspace/rootfs
```

- Step 9: Disconnect the QCOW2 image

```
$ sudo qemu-nbd --disconnect /dev/nbd0
```

Use the modified OVMF.sb.fd and tdx-guest.sb.qcow2 to start a TDVM and verify whether the secure boot is enabled via the dmesg log:

```
$ dmesg | grep -i "Secure Boot"
```

It is expected to show "`Secure Boot Enabled`"

3.4.3 Use VirtIO Device

Within the Intel TDX guest, the drivers are the largest threat attack surface by far. They access the host-controlled PCI config space to perform MMIO and port IO. Refer to Figure 1816: TDX Guest Attack Surface or detail threat analysis at [2].

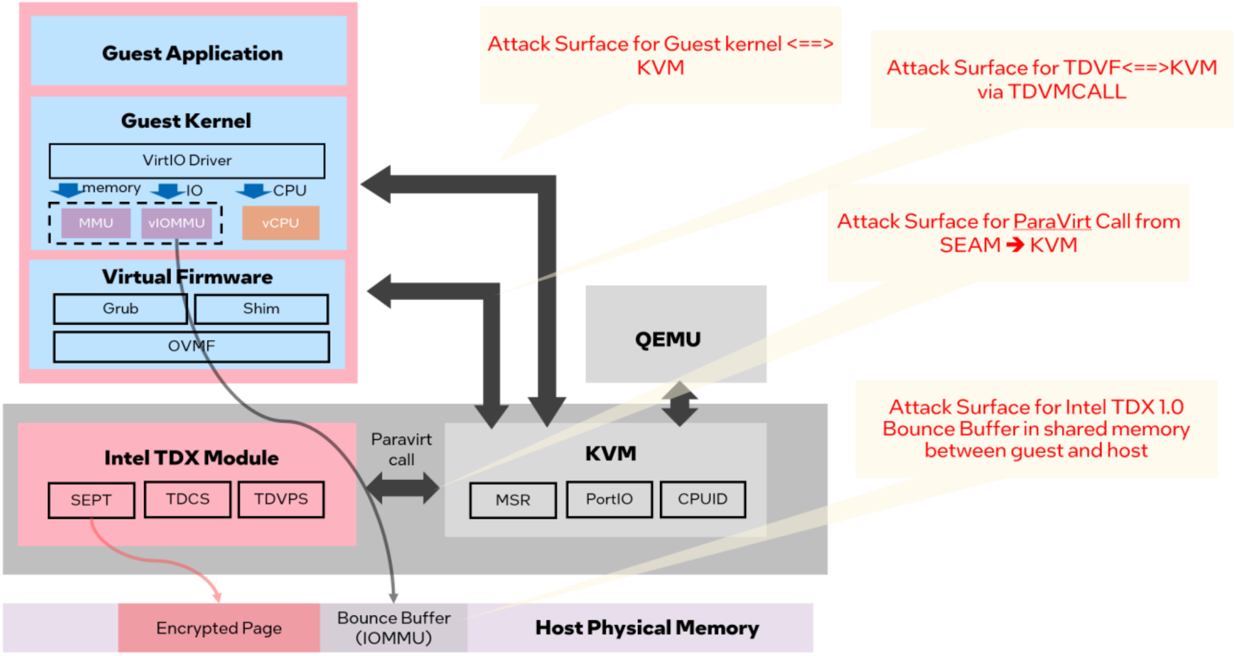

Guest Application
Guest Kernel
VirtIO Driver
memory
IO
CPU
MMU
vIOMMU
vCPU
Virtual Firmware
Grub
Shim
OVMF
Intel TDX Module
SEPT
TDCS
TDVPS
Paravirt call
QEMU
KVM
MSR
PortIO
CPUID
Encrypted Page
Bounce Buffer (IOMMU)
Host Physical Memory
Attack Surface for Guest kernel <==> KVM
Attack Surface for TDVF<==>KVM via TDVMCALL
Attack Surface for ParaVirt Call from SEAM ➔ KVM
Attack Surface for Intel TDX 1.0 Bounce Buffer in shared memory between guest and host

Figure 18: TDX Guest Attack Surface

To mitigate this risk there is a curated list of drivers that are enabled in the runtime for the TD guest kernel. By default, all PCI and ACPI bus drivers are blocked unless they are in the allow-list. The current default allow-list for the PCI bus is limited to the following VirtIO drivers:

- virtio_net
- virtio_console
- virtio_blk
- 9pnet_virtio
- virtio_vsock

Since most of the ACPI tables are not needed for an Intel TDX guest, the implemented ACPI table allow-list limits them to a small, predefined list with a possibility to pass additional tables via a command line option. The current allow-list is limited to the following tables:

- XSDT
- FACP
- DSDT
- FACS
- APIC
- SVKL

- CCEL

3.5 Validation

3.5.1 Overview

The Linux Stack for Intel TDX provides end to end TDX capability across diverse infrastructures like hypervisor and Kubernetes within hypervisor.

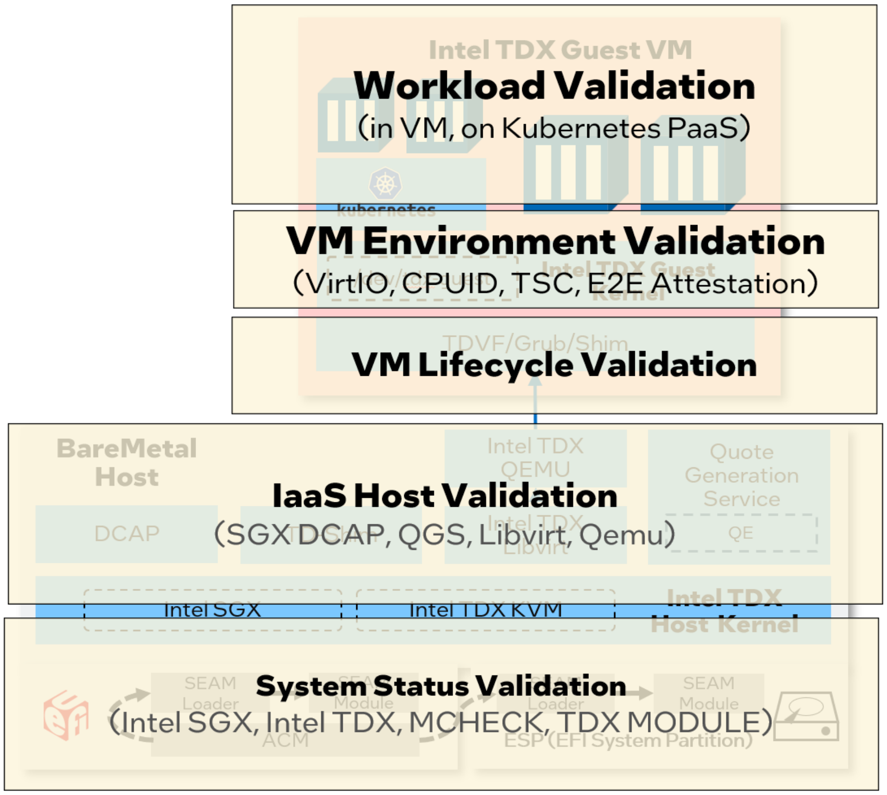


Figure 19: Intel TDX E2E Full Stack Validation

The end-to-end validation of the Linux Stack for Intel TDX covers the following scopes.

Table 5: Linux Stack for Intel TDX Validations

Validation	Scope	Description
System Status	IaaS	Verify the hardware and BIOS status like Intel SGX, Intel TME-MK, Intel TDX, Intel TDX module, etc.
IaaS Host	IaaS	Verify the functionality of IaaS components like platform registration, QGS service, libvirt and QEMU configurations

VM Lifecycle	PaaS	Diverse boot types for TD VM guest, pre-boot environment measurement, etc.
VM Environment	PaaS	CPUID, TSC, VirtIO devices, etc.
Workload	PaaS	Container workloads run in TD guest or the Kubernetes cluster within TD guest

To support complex validation and automation scenarios, the pyCloudStack framework is designed to support the scopes mentioned in **Error! Reference source not found.**.

3.5.2 PyCloudStack

3.5.2.1 Overview

PyCloudStack abstracts the common objects, operations, and resources for diverse cloud architectures. It supports hypervisor stacks based on libvirt or direct QEMU commands, container stacks orchestrated by Kubernetes or directly by docker, and supports running on local or remote IaaS hosts. It can be used to create an advanced deployment CI/CD operator via a Python plugin for an ansible, end-to-end validation, framework with customized components and configurations in a full vertical stack.

The overall architecture diagram is illustrated as below:

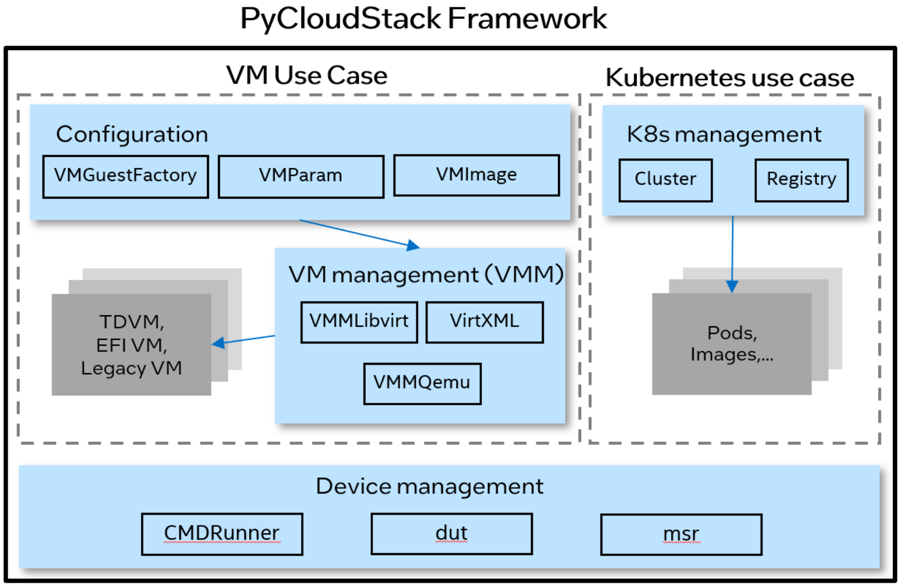


Figure 20: PyCloudStack Framework

The framework supports scenarios for VM management via QEMU direct or via libvirt.

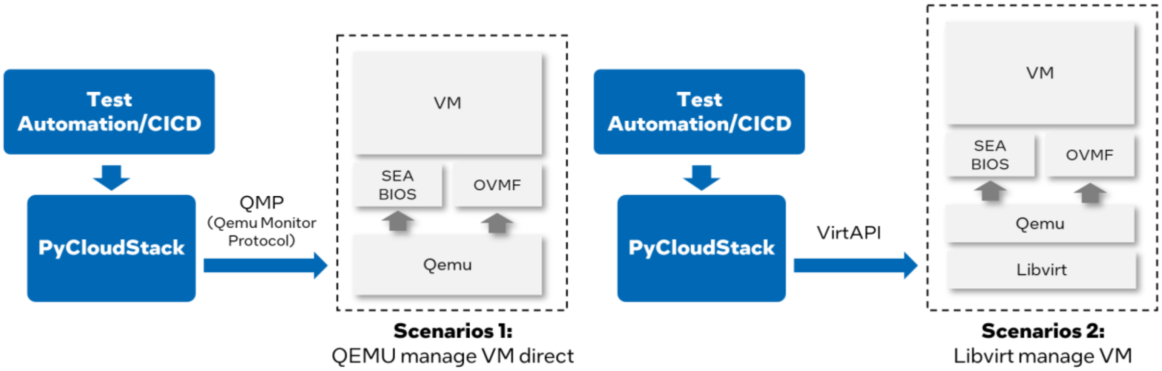


Figure 21: Validation Scenarios for VMM and Libvirt

- Scenario 1: QEMU managed VM directly via QMP (QEMU monitor protocol)[4]
- Scenario 2: Libvirt managed VM via VirtAPI[5]

The framework abstracts the common operations for host, virtual machine, kubernetes, and container:

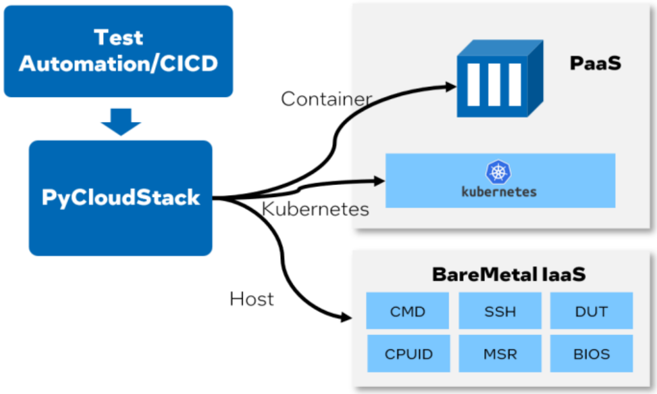


Figure 22: Abstract Common Operations for Cloud Stack

Below are additional details for the VM use case.

- `VMGuestFactory` is designed to communicate and handle VM configurations with test cases. For example, the size of a virtual machine can be specified by indicating how many CPUs and how much memory is required. `VMGuestFactory` usually works with `VMParam` and `VMImage`.

[4] https://wiki.QEMU.org/Documentation/QMP

[5] https://github.com/virtapi/virtapi

    - `VMParam` operator provides predefined VM parameters for typical configuration. It also provides the capability to customize VM parameters.
    - `VMImage` is designed to manage guest images for guest VMs so that multiple guest distros can be supported. Guest images can be customized based on test requirements.
- `VMM` operators are responsible for VM lifecycle management using given configuration. VMM operator includes `VMMLibvirt` and `VMMQEMU`. `VMMLibvirt` needs to work together with "`virtXML`" operator.
- `virtXML` is responsible for Libvirt XML template management. It helps you to customize XML template for VMs.

For Kubernetes use case:

- `cluster` operator is designed to implement Kubernetes object management. `Registry` is used to manage container images. With them working together, you can create Kubernetes objects, such as deployment and service. Then cloud workload can run in a Kubernetes cluster.

There are also some other common operators for Device management at the bottom of the diagram.

- `CMDRunner` is designed to run commands on local host or remote targets via ssh connection.
- `DUT` is designed to manage devices under test, such as CPU frequency of host.
- `MSR` operator provides methods to read and write register.

Finally, with the PyCloudStack framework, functionality, stability, performance, and interoperability tests are well supported.

3.5.2.2 Install PyCloudStack on TDX host

PyCloudStack has been uploaded to [PyPI](). Install PyCloudStack to the host via the following command.

```
$ pip3 install pycloudstack
```

3.5.2.3 Example

Most of automation tests in the tdx-tools repo are based on the PyCloudStack framework. Below are several examples:

- Example 1: Operate VM via Libvirt

```
from pycloudstack.vmguest import VMGuestFactory
from pycloudstack.vmparam import VM_STATE_SHUTDOWN, VM_STATE_RUNNING,
VM_STATE_PAUSE, VM_TYPE_TD

vm_factory = VMGuestFactory(vm_image, vm_kernel)

LOG.info("Create TD guest")
inst = vm_factory.new_vm(VM_TYPE_TD, auto_start=True)
inst.wait_for_ssh_ready()

LOG.info("Suspend TD guest")
inst.suspend()
ret = inst.wait_for_state(VM_STATE_PAUSE)
assert ret, "Suspend timeout"

LOG.info("Resume TD guest")
inst.resume()
ret = inst.wait_for_state(VM_STATE_RUNNING)
assert ret, "Resume timeout"
```

- Example 2: Customize the VM

```
import logging
import psutil
# Get host total cores and sockets, assign 80% vcpu and 80% memory to vm
total_core = psutil.cpu_count()
cores = int(total_core * 0.4)
memsize = int(psutil.virtual_memory().available / 1000 * 0.8)
vmspec = VMSpec(sockets=2, cores=cores, memsize=memsize)
inst = vm_factory.new_vm(VM_TYPE_TD, vmspec=vmspec, auto_start=True)
```

- Example 3: Run TensorFlow AI microbench boosted by AMX within TDVM

```
LOG.info("Create TD guest to test tensorflow")
td_inst = vm_factory.new_vm(vm_type, vmspec=VMSpec.model_large())

# customize the VM image
td_inst.image.inject_root_ssh_key(vm_ssh_pubkey)

# create and start VM instance
td_inst.create()
td_inst.start()
td_inst.wait_for_ssh_ready()

# It may take up to 30 minutes to complete the test
LOG.info("====== The test running may take up to 30 minutes! ======")

command = '''
cd /root/models-2.5.0 && DNNL_MAX_CPU_ISA=AVX512_CORE_AMX OMP_NUM_THREADS=16
KMP_AFFINITY=granularity=fine,verbose,compact
python3 ./benchmarks/launch_benchmark.py
    --model-name dien  --mode inference  --precision bfloat16
    --framework tensorflow --data-location /root/dien
    --exact-max-length=100 --num-inter-threads 1  --num-intra-threads 16
    --batch-size 8 --graph-type=static
    --in-graph /root/dien_fp32_static_rnn_graph.pb
    --benchmark-only --verbose --
     '''
runner = td_inst.ssh_run(command.split(), vm_ssh_key)
assert runner.retcode == 0, "Failed to execute remote command"

# throughput should not be 0
patt_ok = r'Approximate accelerator performance in recommendations/second is
(\d*.\d*)'
match = re.search(patt_ok, '\n'.join(runner.stdout))
assert match is not None
images_per_s = match.group(1)
LOG.info('Throughput: %s recommendations/s', images_per_s)
assert float(images_per_s) > 0
```

3.5.3 Intel TDX Tests

Intel TDX tests from tdx-tools are designed to cover basic acceptance tests, functionality, workload, and environment tests for Intel TDX. It also provides interoperability tests by using AMX in an Intel TDX guest VM.

NOTE: The tests implementation depends on the PyCloudStack framework. The test execution must be on an Intel TDX-enabled Linux platform with an Intel TDX-enabled kernel with QEMU and Libvirt installed.

NOTE: Please make sure to use the correct tag of tdx-tools which matches the release version so that the tests can work with different Intel TDX kernel and Intel TDX QEMU versions.

3.5.3.1 Overview

The tests can be classified into 4 categories – Lifecycle, Environment, Workload and Interoperability. Refer to the test list in the table below. Some of the tests require a customized guest image before running the test. The required prerequisites are in the next section.

Table 6: TDX Stack Tests

Category	Test case	Description
Lifecycle	test_tdvm_lifecycle.py	TD lifecycle management
	test_multiple_tdvms.py	Co-existence of multiple TDs
	test_vm_coexists.py	Co-existence 0f TD and legacy VM
	test_max_cpu.py	Boot TD with high CPU utilization
	test_vm_shutdown_mode.py	Different shutdown modes of Libvirt
	test_acpi_reboot.py	TD ACPI reboot

	test_acpi_shutdown.py	TD ACPI shutdown
	test_vm_shutdown_qga.py	VM shutdown via QEMU guest agent
	test_vm_reboot_qga.py	VM reboot via QEMU guest agent
Environment	test_tdvm_tsc.py	TD TSC clock source and frequency
	test_tdx_guest_status.py	TDX initialization in TD guest
	test_tdx_host_status.py	Check TDX host status
	test_tdvm_network.py	Check network functions in TD
Workload	test_workload_redis.py	Redis workload running in TD
	test_workload_nginx.py	Nginx workload running in TD
Interoperability	test_amx_docker_tf.py	Run AI model with AMX in docker container on TD
	test_amx_vm_tf.py	Run AI model with AMX in TD

A full example for a redis workload test case is as follows. You can find the complete test case in `tdx-tools/tests/tests/test_workload_redis.py`.

```
def test_tdvm_redis(vm_factory, vm_ssh_pubkey, vm_ssh_key):
    """
    Run redis benchmark test
    Ref: https://redis.io/topics/benchmarks
    Use official docker images redis:latest
    Test Steps:
    1. start VM
    2. Run remote command "systemctl status docker" to check docker service's
status
    3. Run remote command "systemctl start docker" to force start docker service
    4. Run remote command "/root/bat-script/redis-bench.sh"
       to launch redis container and  benchmark testing
    """
    LOG.info("Create TD guest to run redis benchmark")
    td_inst = vm_factory.new_vm(VM_TYPE_TD)

    # customize the VM image
    td_inst.image.inject_root_ssh_key(vm_ssh_pubkey)
    td_inst.image.copy_in(
        os.path.join(CURR_DIR, "redis-bench.sh"), "/root/")

    # create and start VM instance
    td_inst.create()
    td_inst.start()
    td_inst.wait_for_ssh_ready()

    command_list = [
        'systemctl start docker',
        '/root/redis-bench.sh -t get,set'
    ]
    for cmd in command_list:
        LOG.debug(cmd)
        runner = td_inst.ssh_run(cmd.split(), vm_ssh_key)
        assert runner.retcode == 0, "Failed to execute remote command"
```

3.5.3.2 Prerequisites

A guest image is required for all the tests. Refer to "Chapter 2.4.2 Create Guest Image" to generate a basic guest image. Additional prerequisites are required for some of the tests. The first step is to start a VM using the guest image built above and go through corresponding items required by tests. The next step is to shut down the VM and use the guest image for further tests.

1. Install QEMU guest agent in guest image.

   For Ubuntu 22.04 guest image:

```
$ sudo apt-get install qemu-guest-agent
```

   For RHEL 8.x guest image:

```
$ sudo dnf install qemu-guest-agent
```

2. Install docker in guest image.

   For Ubuntu 22.04 guest image:

```
$ sudo apt-get install docker.io
```

   For RHEL 8.x guest image:

```
$ sudo dnf install docker
```

3. For workload tests, make sure the latest docker image is in the guest image. It needs both the docker image "nginx:latest" and "redis:latest".

```
$ docker pull nginx:latest
$ docker pull redis:latest
```

4. Install `intel-tensorflow-avx512` in guest image. Download the DIEN_bf16 model and put it under /root in the guest image.

   For ubuntu 22.04 guest image:

```
$ pip3 install intel-tensorflow-avx512==2.11.0
$ wget https://storage.googleapis.com/intel-optimized-
tensorflow/models/v2_5_0/dien_bf16_pretrained_opt_model.pb
```

For RHEL 8.x guest image upgrade python to python 3.8 first and then run the following commands:

```
$ pip3 install intel-tensorflow-avx512==2.11.0
$ wget https://storage.googleapis.com/intel-optimized-
tensorflow/models/v2_5_0/dien_bf16_pretrained_opt_model.pb
```

3.5.3.3 Setup Environment

1. Install required packages:

   If your host distro is RHEL 8.x:

```
$ sudo dnf install python3-virtualenv python3-libvirt libguestfs-devel libvirt-
devel python3-devel gcc gcc-c++
```

   If your host distro is Ubuntu 22.04:

```
$ sudo apt install python3-virtualenv python3-libvirt libguestfs-dev libvirt-dev
python3-dev net-tools
```

2. Make sure the libvirt service is started. If not, start libvirt service. If the host is Ubuntu 22.04 and AppArmor is enabled, set `security_driver = "none"` in `/etc/libvirt/qemu.conf` and restart the libvirt service.

```
$ sudo systemctl status libvirtd
$ sudo systemctl restart libvirtd
```

3. Setup environment. Run the below command to setup the python environment.

```
$ cd tdx-tools/tests/
$ source setupenv.sh
```

4. Create artifacts.yaml from template

   Refer template `<tdx-tools>/tests/artifacts.yaml.template` to create `<tdx-tools>/tests/artifacts.yaml`. Update
   the source and sha256sum to indicate the location of guest image and guest kernel. See following example:

```
latest-guest-image-rhel:
  source: http://cpss-devops.sh.intel.com/download/tdx-guest/latest/td-guest-
rhel8.7.qcow2.tar.xz
  sha256sum: http://css-devops.sh.intel.com/download/tdx-guest/latest/td-guest-
rhel8.7.qcow2.tar.xz.sha256sum
```

```
latest-guest-kernel-rhel:
  source: http://css-devops.sh.intel.com/download/tdx-guest/latest/vmlinuz-rhel8.7
  sha256sum: http://css-devops.sh.intel.com/download/tdx-guest/latest/vmlinuz-
rhel8.7.sha256sum

latest-guest-image-ubuntu:
  source: http://css-devops.sh.intel.com/download/tdx-guest/latest/td-guest-
ubuntu-22.04-test.qcow2.tar.xz
  sha256sum: http://css-devops.sh.intel.com/download/tdx-guest/latest/td-guest-
ubuntu-22.04-test.qcow2.tar.xz.sha256sum

latest-guest-kernel-ubuntu:
  source: http://css-devops.sh.intel.com/download/tdx-guest/latest/vmlinuz-jammy
  sha256sum: http://css-devops.sh.intel.com/download/tdx-guest/latest/vmlinuz-
jammy.sha256sum
```

5. Generate keys

   Generate a pair of keys that will be used in test running.

```
$ ssh-keygen
```

   The keys should be named "vm_ssh_test_key" and "vm_ssh_test_key.pub" and located under tdx-tools/tests/tests/

3.5.3.4 Run Tests

1. Run all tests:

```
$ sudo ./run.sh -s all
$ # NOTE:
$ # "sudo" is required since some tests need root permission.
$ # The user needs to be added into the libvirt group. e.g., for user "root"
$ # please run
$ sudo usermod -aG libvirt root
```

2. Run some case modules:

```
$ ./run.sh -c <test_module1> -c <test_module2>
```

   For example, run the whole test module "test_tdvm_lifecycle.py".

```
$ ./run.sh -c tests/test_tdvm_lifecycle.py
```

3. Run specific test cases:

```
$ ./run.sh -c <test_module1> -c <test_module1>::<test_name>
```

   For example, run the test case "test_tdvm_lifecycle_virsh_start_shutdown" in "tests/test_tdvm_lifecycle.py"

```
$ ./run.sh -c tests/test_tdvm_lifecycle.py::
test_tdvm_lifecycle_virsh_start_shutdown
```

4. User can specify guest image OS type with “-g”. Currently “rhel” and “ubuntu” are supported. RHEL 8.x guest image will be used by default if “-g” is not specified.

   For example, run all the tests using an Ubuntu 22.04 guest image.

```
$ sudo ./run.sh -g ubuntu -s all
```

4 Measurement & Attestation

Remote attestation enables a relying party (either the owner of a workload or a user of the services provided by a workload) to establish that the workload is running on an Intel-TDX-enabled platform within a TD prior to providing data to the workload. TD measurements collect the information of hardware, firmware and software about TD, which will be extended to TD measurement registers and be part of TD REPORT for remote attestation. In this section, it will introduce TDX measurement and remote attestation process.

4.1 TEE, TCB, Quote

Typically, a TEE provides the evidence or measurements of its origin and current state so that the evidence can be verified by another party either programmatically or manually. It can decide whether to trust code running in the TEE. It is typically important that such evidence is signed by hardware that can be vouched for by a manufacturer, so that the party checking the evidence has strong assurances that it was not generated by malware or other unauthorized parties. [3] The remote party allows sending the secret or key to the TEE environment after successfully verifying the evidence.

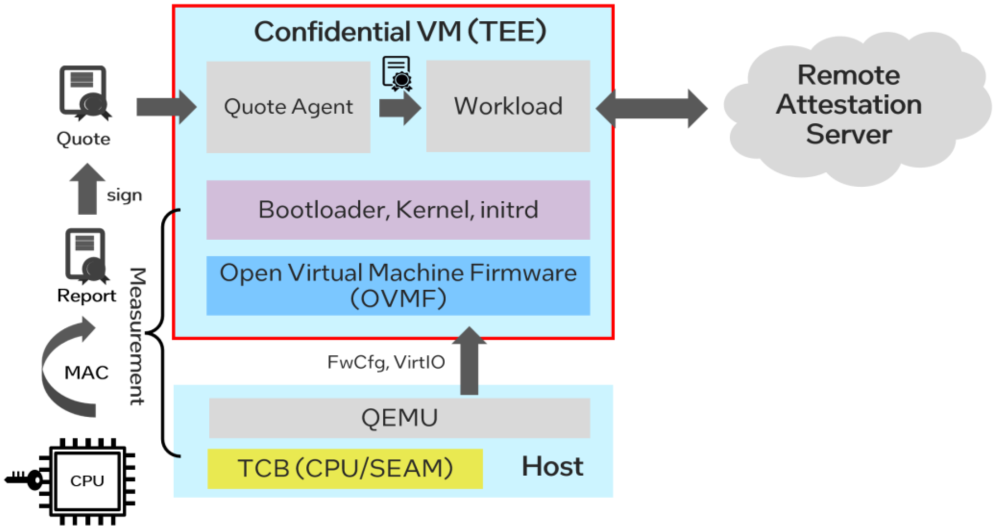


Figure 23: Measurement and Attestation for TEE

The trusted computing base (TCB) refers to all of a system's hardware, firmware, and software components that provide a secure environment. For a confidential VM, it includes hardware information such as CPU, SEAM firmware, and guest components such as OVMF, bootloader (shim/grub), and kernel. The other host software such as QEMU VMM and Orchestrator Libvirt are out of TCB.

The hash-chained measurement on TCB will be extended to some secure registers such as TPM PCR (platform configuration register). The values from several secure registers construct to a report and are finally signed to be a quote by an attestation key.

4.2 TDX Measurement

4.2.1 TD Report

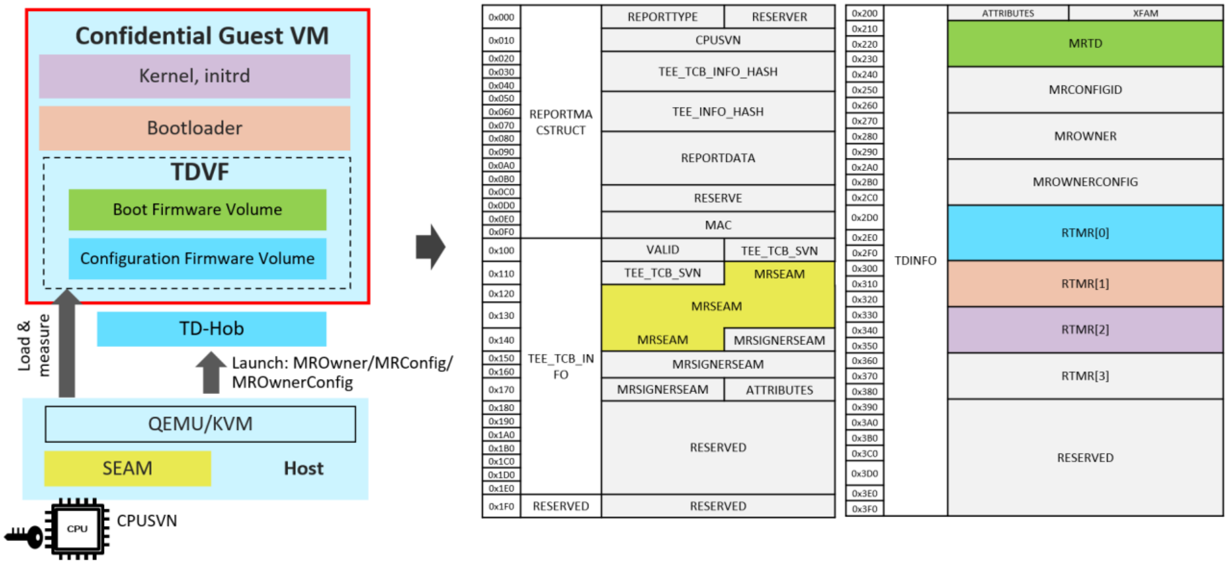


Figure 24: Intel TDX Measurement

The API TDG.MR.REPORT in the Intel TDX module creates a TDREPORT_STRUCT structure[6] containing the TD measurements, initial configuration of the TD that was locked at finalization (TDH.MR.FINALIZE), the Intel TDX module measurements, and the REPORTDATA value [1]:

- The measurement of TDX module is recorded in the field MRSEAM.
- The measurement of TDVF/OVMF is record in the field MRTD.
- The measurement of TD-Hob, ACPI is record in the RTMR [0].
- The measurement of bootloaders like grub/shim is recorded in the field RTMR [1].

[6] https://github.com/tianocore/edk2/blob/master/MdePkg/Include/IndustryStandard/Tdx.h

- The measurement of kernel and initrd is recorded in the field RTMR [2].

NOTE: for direct boot, there is no bootloader, so the measurement of kernel is recorded in the field RTMR [1].

4.2.2 MRTD and RTMR

There are two types of measurement registers – MRTD and RTMR for Intel TDX:

- MRTD (TD measurement register) provides static measurement of TD build process and the initial contents of TD
- RTMR (runtime measurement register) is an array of general-purpose measurement registers to Intel TDX software to enable measuring additional logic and data loaded into the TD at runtime. As designed, RTMR can be used by the guest TD software to measure the boot process.

There are 4 RTMR registers:

Table 7: RTMR Definitions

Register	Content	Measured by
`RTMR [0]`	Static configuration (CFV); Dynamic Configuration (TD HOB, ACPI)	TDVF
`RTMR [1]`	PCI option ROM, OS loader, OS kernel, initrd, GPT, boot variable, boot parameter	TDVF
`RTMR [2]`	TD OS App	OS applications
`RTMR [3]`	Reserved	

4.2.3 Pre-Boot Measurement

The pre-boot environment before the kernel includes the TDVF/OVMF phase of the bootloader phase (shim and grub). The whole boot chain will be measured into RTMR via `EFI_CC_MEASUREMENT_PROTOCOL`[7].

[7] https://github.com/tianocore/edk2/blob/master/MdePkg/Include/Protocol/CcMeasurement.h

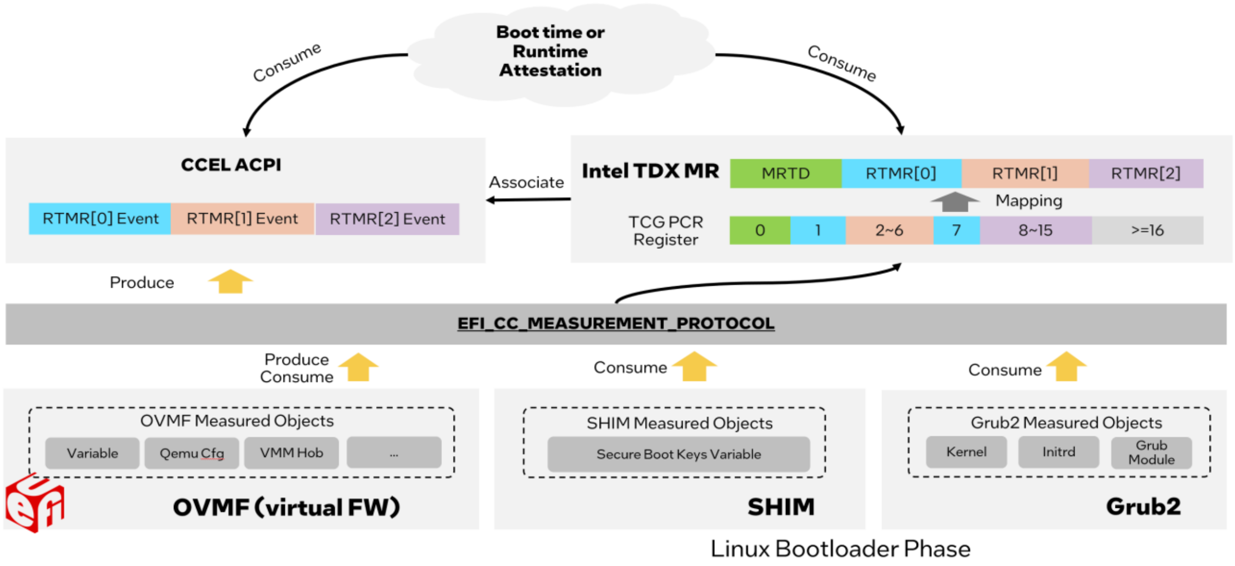


Figure 25: TD Measurement Process

Similar to the TCG event log [4], `EFI_CC_MEASUREMENT_PROTOCOL` logs the events into ACPI table CCEL [8] and the measurement hash is extended to the corresponding RTMR register. The event logs in CCEL table can be replayed within a TD guest to verify the RTMR value.

4.2.4 PyTdxMeasure Tool

PyTdxMeasure in tdx-tools provides a Python library and utilities for TD measurement that can be used by tenant workloads, attestation agents, or validation tools:

- Get RTMR value from TDREPORT via Linux attestation driver.
- Get the full TD event log from CCEL ACPI table.
- Verify value of RTMR by replaying event logs.

Here are the step-by-step instructions to use PyTdxMeasure:

- Install

```
$ python3 -m pip install pytdxmeasure
```

- Run
  - Get Event Log.

```
$ tdx_eventlogs
```

[8] https://uefi.org/specs/ACPI/6.5/05_ACPI_Software_Programming_Model.html#cc-event-log-acpi-table

Refer to the example outputs at measurement log for grub boot and measurement log for direct boot

- Get TDREPORT, which includes value of RTMR.

```
$ tdx_tdreport
```

- Verify RTMR.

```
$ tdx_verify_rtmr
```

The tool will compare RTMR value from TDREPORT and RTMR value replayed via event log. The two values are expected to be identical, which means the measured contents are not tampered with.

4.2.5 Linux Runtime Measurement

Integrity Measurement Architecture (IMA) is the Linux kernel integrity subsystem to detect if files have been accidentally or maliciously altered, both remotely and locally. Currently, IMA maintains the runtime measurement list, if anchored in a hardware Trusted Platform Module (TPM), to make the measured hashes of files immutable. It also supports the appraise mechanism to enforce local file integrity by appraising the measurement against a "good" value stored as an extended attribute.

Extra kernel changes have been introduced to enable IMA in a TD guest and to maintain the runtime measurement list inside of an RTMR [2].

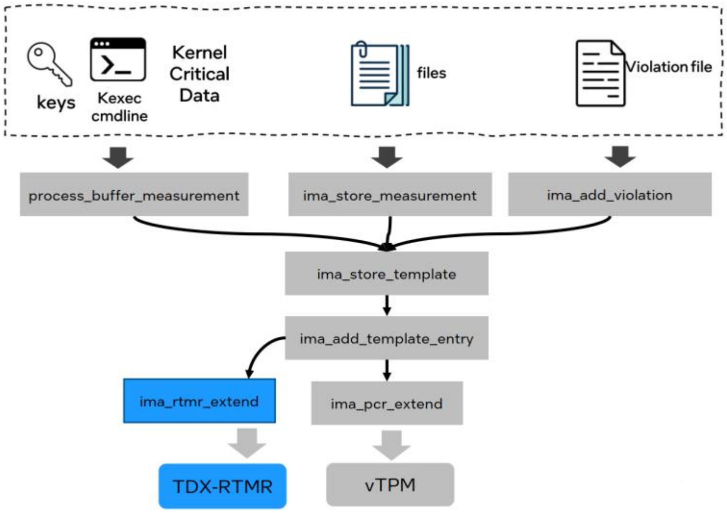


Figure 26: Enable IMA extend hash to RTMR

Different configurations (kernel command line) can be applied to define the scope to be measured. Available options include:

- "`ima_hash=sha384`": Enable measurement against boot aggregates, which covers firmware, boot loader, kernel command line and etc.
- "`ima_hash=sha384 ima_policy=critical_data`": Enable measurements against boot aggregates and kernel integrity critical data.
- "`ima_hash=sha384 ima_policy=tcb`": Enable measurements against all programs executed, files mmap'd for execution, and all files opened with the read mode bit set by either the effective uid (euid=0) or uid=0.

Custom policies can be set by the user to define the scope to be measured. For more details, please refer to the IMA documentation.

Below are some sample instructions to enable and verify this feature in a TD guest:

- Sample configuration to start up the TD VM

```
$ ./start-qemu.sh -k <path-to-kernel> -i <path-to-image> -e
"ima_hash=sha384 ima_policy=critical_data"
```

- Run
  - Get IMA measurement count.

```
$ sudo cat /sys/kernel/security/integrity/ima/runtime_measurements_count
```

  - Get full IMA measurement list stored inside the kernel securityfs.

```
$ sudo cat /sys/kernel/security/integrity/ima/ascii_runtime_measurements
```

  - Verify RTMR within TDREPORT by using the PyTdxMeasure Tool.

```
$ sudo ./tdx_tdreport
```

User can find the measurements extended in RTMR [2] inside the TDREPORT. TPM PCR Calculator (available in Microsoft Store) can be used to replay the result with the ASCII measurements that fetched inside kernel security FS.

4.3 Attestation

4.3.1 Overview

Remote attestation helps an off-platform party (also known as Relying Party) to have increased confidence that the software is running inside a TD, on a genuine, Intel-TDX system, and at a given security level (also referenced as the TCB version).

On a high level, the Relying Party requests attestation proof – a TD Quote – and then verifies this TD Quote. Among other information, the TD Quote contains: TD measurements (static and runtime), data that the TD associates with itself, SVNs of elements in the TDX TCB. Intel TDX attestation requires Intel SGX, because an SGX-based TD-Quoting Enclave is used in the process. In the following, we provide some more details of the Intel SGX attestation flow. See Section E of Intel® Trust Domain Extension – White Paper for more details about Intel TDX remote attestation.

Intel TDX Attestation flow (see Figure 2722):

- (1): Relying Party sends an attestation request to TD.

- (2): TD requests a TD Report from the Intel TDX Module

- (3, 4): Intel TDX Module invokes the CPU instruction SEAMREPORT, which triggers the hardware-based generation of a TD Report including, among other information, TD measurements (static and runtime), data that the TD associates with itself, SVNs of elements in the TDX TCB. The SEAMREPORT instruction protects the integrity of the TD Report with a MAC for which the key is only known to hardware.

- (5): Intel TDX Module passes back the TD Report to the TD.

- (6): TD forwards the TD Report to the VMM requesting the conversion to a TD Quote.

- (7, 8): VM forwards the TD Report to the TD Quoting Enclave for conversion. TD Quoting Enclave uses the CPU instruction EVERIFYREPORT2 to verify the MAC of the TD Report. On success, the TD Quoting Enclave converts the TD Report to a TD Quote by signing the TD Report with its Attestation Key. The Attestation Key is signed with the Provisioning Certificate Key (PCK) by the Provisioning Certification Enclave (PCE) and the Intel publishes certificates and certificate revocation lists for PCKs. As a result, the trust of TD Quotes is rooted in Intel CAs.

- (9, 10): VMM passed back TD Quote to TD, and TD forwards it to the challenger.

- (11, 12): Relying Party performs attestation verification by verifying the TD Quote. The attestation verification can be done by the Relying Party itself or using a dedicated attestation service, e.g., Project Amber.

Intel TDX remote attestation demonstrates applications that are running securely on a given trusted environment (TD guest) to a relying party. This increases the confidence of a remote party that the software is running inside a TD on a genuine Intel TDX system at a given security level, which is also referenced as the TCB version. The TDX attestation reuses Intel SGX infrastructure to provide attestation to a given measurement. It is based on TD Quote, which is the signed TD Report in TD Quoting Enclave [1].

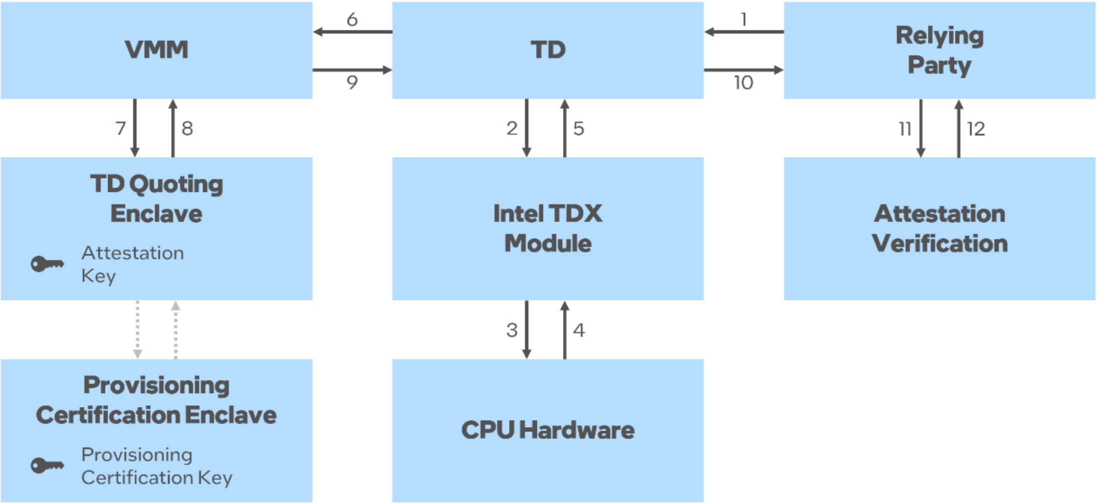


Figure 27: Intel TDX Attestation Flow

The Linux Stack for Intel TDX 1.5 provides end-to-end Intel TDX attestation capability by integrating the Intel® Software Guard Extensions Data Center Attestation Primitives[9] (Intel® SGX DCAP). In this section, it will introduce how to run Intel TDX remote attestation.

NOTE: Since TDX module 1.5 has no production-signed version yet, TDX attestation in Linux Stack for Intel TDX 1.5 will use SBX server. The corresponding URL and configuration will be based on SBX server as well.

4.3.2 Set Up DCAP Repository on Host

In the following, we show how to set up Intel SGX DCAP on an Intel TDX host with either Ubuntu 22.04 or RHEL 8.x. For more details about installation and self-building https://download.01.org/intel-sgx/sgx-dcap/1.18/linux/docs/ or https://github.com/intel/SGXDataCenterAttestationPrimitives

[9] https://github.com/intel/SGXDataCenterAttestationPrimitives

Before running the steps, download SGX DCAP archive 1.18 from https://download.01.org/intel-sgx/sgx-dcap/1.18/linux/ according to your OS distro. The relevant archive is named sgx_*_local_repo.tgz.

This example shows how to set up the package repository on an Intel TDX host with either Ubuntu 22.04 or RHEL 8.x.

1. Ubuntu 22.04
    a. Setup DCAP repo

```
$ # Prepare DCAP repo
$ tar zxvf sgx_debian_local_repo.tar.gz
$ sudo mv sgx_debian_local_repo /srv/sgx_debian_local_repo

$ # Set up local Debian repository
$ sudo cat <<EOF >> /etc/apt/sources.list.d/sgx_debian_local_repo.list
deb [trusted=yes arch=amd64] file:/srv/sgx_debian_local_repo jammy main
EOF
$ sudo apt update
```

    b. Install dependencies.

```
$ sudo apt install -y gcc make tar

 # Install latest nodejs, version 18 shown below is an example
$ curl -sL https://deb.nodesource.com/setup_18.x -o nodesource_setup.sh
$ sudo bash nodesource_setup.sh
$ sudo apt-get install -y nodejs
```

2. RHEL 8.x
    a. Setup DCAP repo

```
$ # Prepare DCAP repo
$ tar zxvf <RDC_DOWNLOAD_DIR>/<DCAP_DIR>/RHEL8.6/sgx_rpm_local_repo.tar.gz
$ mv sgx_rpm_local_repo /srv/sgx_rpm_local_repo
$
$ # Set up local RPM repository
$ sudo cat <<EOF >> /etc/yum.repos.d/tdx-attestation.repo
[tdx-attestation-local]
name=tdx-attestation-local
baseurl=file:///srv/sgx_rpm_local_repo
enabled=1
gpgcheck=0
module_hotfixes=true
EOF
$
$ sudo dnf check-update
```

    b. Install dependencies.

```
$ sudo dnf install -y gcc make tar

$ sudo dnf module reset nodejs
```

```
$
$ # Install latest nodejs, version 18 shown below is an example
$ sudo dnf module install nodejs:18
```

4.3.3 Set Up PCCS on Host

Intel provides a reference implementation of the Provisioning Certification Caching Service (PCCS). This cache can store collateral (e.g., Provisioning Certificate Key certificates and TCB levels) necessary for TD quote generation and TD quote verification, without the need to access the Intel® Software Guard Extensions Provisioning Certification Service (Intel® SGX PCS).

In the following example, we assume you use Intel's PCCS implementation for remote attestation purposes.

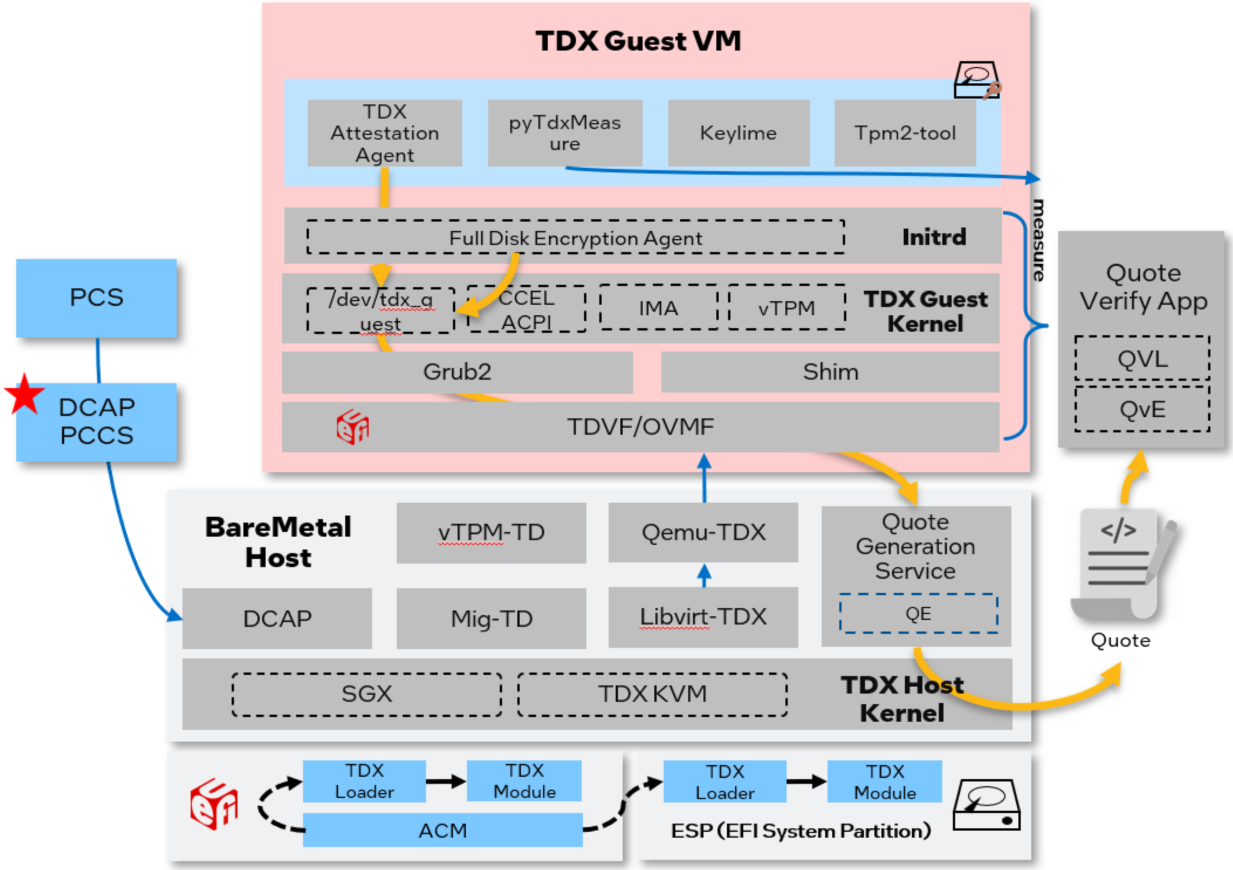


Figure 28: Setup PCCS

1. Obtain a provisioning API key for to enable the PCCS RESTful API.

   Go to https://sbx.api.portal.trustedservices.intel.com/provisioning-certification and click 'Subscribe'. An API key will be generated. Copy the API key for the following steps.

2. Install PCCS with following steps. During installation, answer "Y" when asked if the PCCS should be installed now, "Y" when asked if PCCS should be configured now, and enter API key generated in step 1 when asked for "Intel PCS API key". Answer the remaining questions according to your needs.

   - Ubuntu 22.04

```
$ # Switch to root user for installation
$ sudo su
$
$ apt update
$ apt install -y --no-install-recommends sgx-dcap-pccs
```

NOTE: If you have configured PCCS during above installation command, it doesn't need to run below install.sh which will configure PCCS again.

```
$ cd /opt/intel/sgx-dcap-pccs
$ sudo -u pccs ./install.sh
```

   - RHEL 8.x

```
$ # Switch to root user for installation
$ sudo su
$
$ dnf install -y sgx-dcap-pccs
```

NOTE: If you have configured PCCS during above installation command, it doesn't need to run below install.sh which will configure PCCS again.

```
$ cd /opt/intel/sgx-dcap-pccs
$ sudo -u pccs ./install.sh
```

3. After the installation is completes successfully, make sure the PCCS is configured to use the v4 API. Look for "uri" in the configuration file `/opt/intel/sgx-dcap-pccs/config/default.json`:

```
"uri": "https://sbx.api.trustedservices.intel.com/sgx/certification/v4/"
```

4. If present, delete the old PCCS database, Afterwards, restart PCCS

```
$ [Optional] Remove old PCCS datase
$ sudo rm -rf /opt/intel/sgx-dcap-pccs/pckcache.db
```

```
$
$ Restart PCCS and check status
$ sudo systemctl restart pccs
$ sudo systemctl status pccs
```

You can check the PCCS service log with the following command:

```
$ sudo journalctl -u pccs -f
```

4.3.4 Set Up Quote Generation Service on Host

This section introduces how to install Quote Generation Service (QGS) and how to perform Intel SGX platform registration.

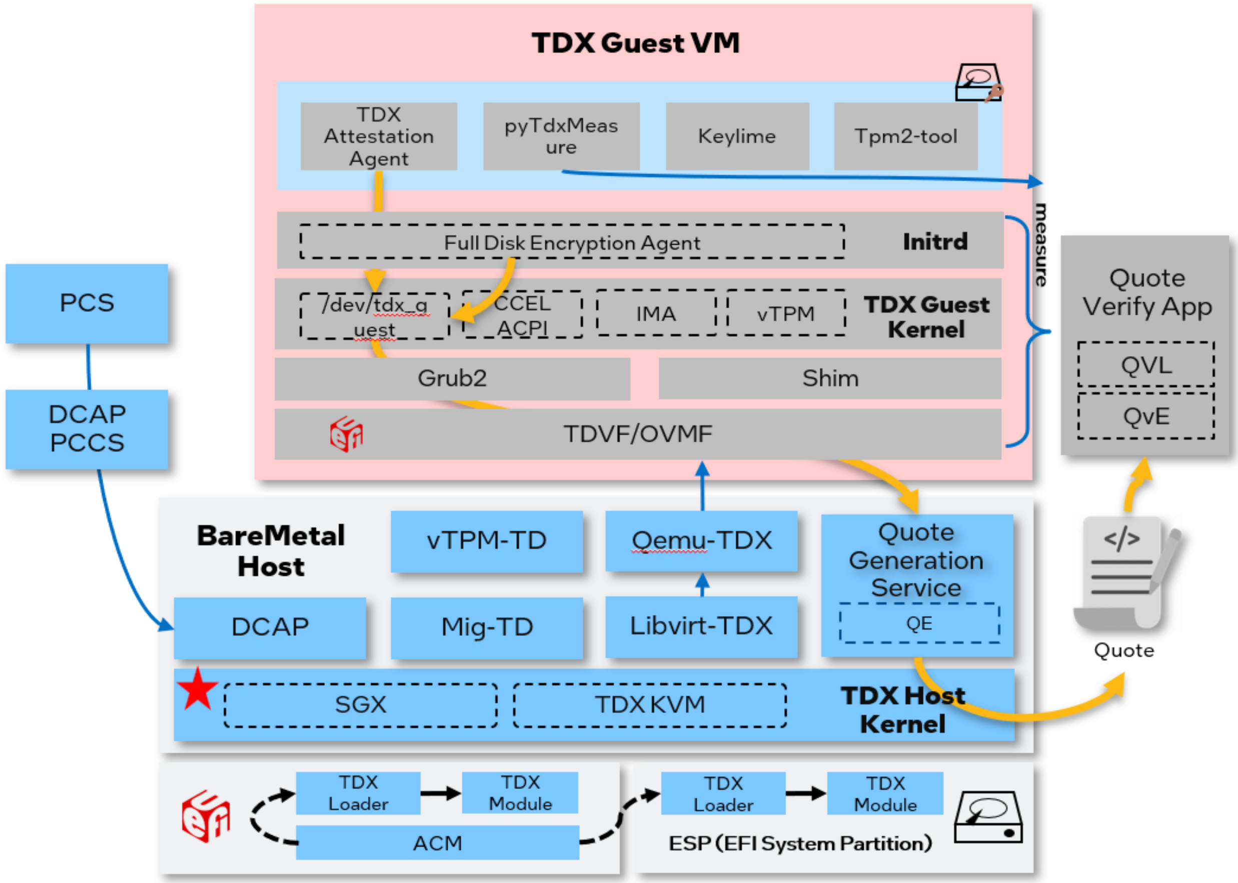


Figure 29: Set up DCAP software on the TDX host

1. Download the Intel® Software Guard Extensions SDK for Linux* OS (Intel® SGX SDK for Linux* OS) from https://download.01.org/intel-sgx/sgx-dcap/1.18/linux/distro/ according to your OS distro. The relevant archive is named `sgx_linux_x64_sdk_*.bin`.

2. Install the Intel® Software Guard Extensions SDK for Linux* OS (Intel® SGX SDK for Linux* OS) to the folder `/opt/intel/`

   - Ubuntu 22.04 host

```
$ sudo chmod +x sgx_linux_x64_sdk_2.19.90.3.bin
$ sudo ./sgx_linux_x64_sdk_2.19.90.3.bin
```

   - RHEL 8.x host.

```
$ sudo chmod +x sgx_linux_x64_sdk_2.19.90.3.bin
$ sudo ./sgx_linux_x64_sdk_2.19.90.3.bin
```

3. Install QGS and QPL packages on the host.

   - Ubuntu 22.04 host

```
$ sudo apt install -y --no-install-recommends tdx-qgs libsgx-dcap-default-qpl
libsgx-dcap-default-qpl-dev
```

   - RHEL 8.x host

```
$ sudo dnf install -y tdx-qgs libsgx-dcap-default-qpl libsgx-dcap-default-qpl-
devel
```

NOTE: If you didn't provide secure certificate for PCCS HTTPS service, please modify the configuration file: `/etc/sgx_default_qcnl.conf` *to add the following.*

```
// PCCS server address
“pccs_url”: “https://<PCCS_IP>:8081/sgx/certification/v4/”,
// To accept insecure HTTPS certificate depends on PCCS Server’s configuration,
// set below option to false
“use_secure_cert”: false
```

4. Install PCKIDRetrievalTool

   - Ubuntu 22.04 host

```
$ sudo apt install -y sgx-pck-id-retrieval-tool
```

   - RHEL 8.x host

```
$ sudo dnf install -y sgx-pck-id-retrieval-tool
```

NOTE: the reported version of the PCKIDRetrievalTool may be different, if you didn't provide secure certificate for PCCS HTTPS service, please modify the configuration file `/opt/intel/sgx-pck-id-retrieval-tool/network_setting.conf` *with the following content.*

```
PCCS_URL=https://<PCCS_IP>:8081/sgx/certification/v4/platforms
# if using localhost as pccs
# PCCS_URL=https://localhost:8081/sgx/certification/v4/platforms
USE_SECURE_CERT=FALSE
```

5. Do SGX platform Registration via PCKIDRetrievalTool

```
$ cd /opt/intel/sgx-pck-id-retrieval-tool
$ sudo sh -c ./PCKIDRetrievalTool
```

The expected response is as follows. The reported version may be different.

```
Intel® Software Guard Extensions PCK Cert ID Retrieval Tool Version 1.18.100.1
Registration status has been set to completed status. Pckid_retrieval.csv has been
generated successfully!
```

NOTE: If it returns a message like "Platform Manifest not available", you may need to perform a SGX Factory Reset in BIOS and run PCKIDRetrievalTool again.

4.3.5 Generate Quote in TD

This section introduces the quote generation steps including launching a TDX guest with quote generation support and generating a quote within the TDX guest.

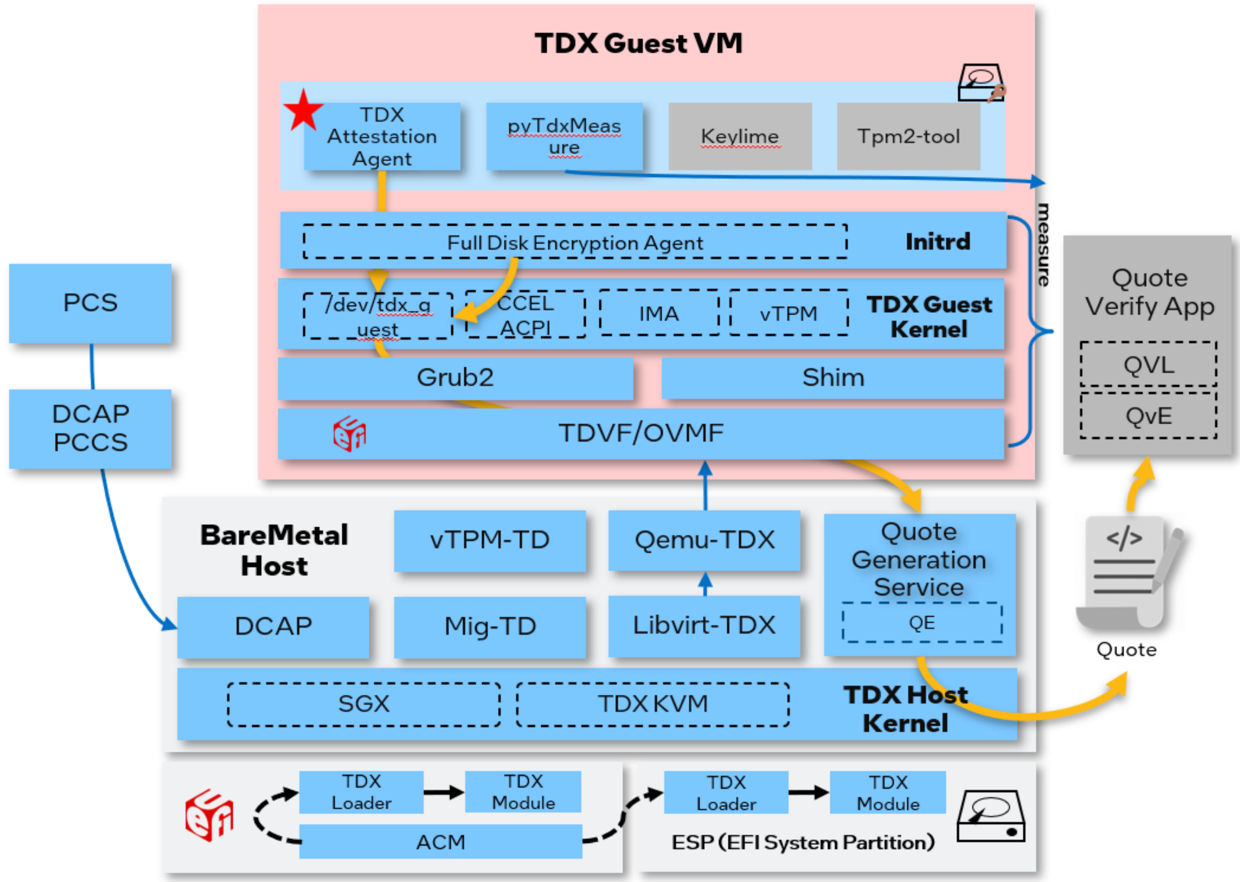


Figure 30: Quote Generation

4.3.5.1 Launch TD with Quote Generation Support

There are two ways to run quote generation: get quote via vsock or get quote via TDVMCALL. Both are supported.

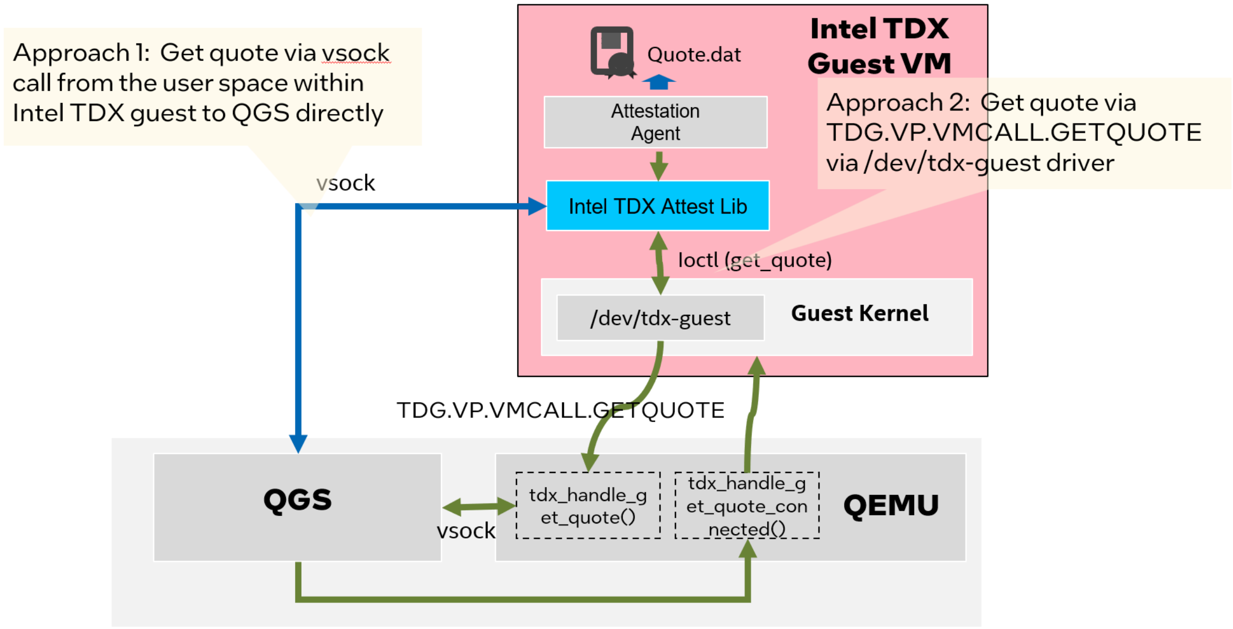

Approach 1: Get quote via vsock call from the user space within Intel TDX guest to QGS directly
Quote.dat
Intel TDX Guest VM
Attestation Agent
Approach 2: Get quote via TDG.VP.VMCALL.GETQUOTE via /dev/tdx-guest driver
vsock
Intel TDX Attest Lib
Ioctl (get_quote)
/dev/tdx-guest
Guest Kernel
TDG.VP.VMCALL.GETQUOTE
QGS
tdx_handle_get_quote()
tdx_handle_get_quote_connected()
QEMU
vsock

Figure 31: Approaches to Generate Intel TDX Quote

- Approach 1: Get quote via vsock call from the user space within TD guest to QGS directly.
  - If launched via QEMU, add the following parameter.

```
-device vhost-vsock-pci,guest-cid=3
```

  - If using start-qemu.sh to indicate getting quote via vsock.

```
$ ./start-qemu.sh -i <guest image> -k <guest kernel> -q vsock
```

  - If launched via Libvirt, add the following fields in XML

```
<vsock model='virtio'>
  <cid auto='yes' address='3'/>
  <address type='pci' domain='0x0000' bus='0x05' slot='0x00' function='0x0'/>
</vsock>
```

- Approach 2: Get quote via `TDG.VP.VMCALL.GETQUOTE`
  - If launched via QEMU, add "`quote-generation-service=vsock:2:4050`" in parameter -object

```
-object tdx-guest,sept-ve-disable,id=tdx,quote-generation-service=vsock:2:4050
```

  - If using start-qemu.sh to indicate getting quote via tdvmcall.

```
$ ./start-qemu.sh -i <guest image> -k <guest kernel> -q tdvmcall
```

  - If launched via libvirt, add following fields in XML

```
<launchSecurity type='tdx'>
  ......
  <Quote-Generation-Service>vsock:2:4050</Quote-Generation-Service>
</launchSecurity>
```

- Within a TD guest, create a file at `/etc/tdx-attest.conf` with the following content:

```
port=4050
```

4.3.5.2 Generate Quote within Intel TDX Guest

1. Set up the package repository in TD guest. Refer to steps of "Setup DCAP repo" in section 4.3.2 Set Up DCAP Repository on Host:

- Install `libtdx-attest, libtdx-attest-dev`
  - For Ubuntu 22.04

```
$ sudo apt install -y libtdx-attest libtdx-attest-dev
$ sudo apt-get install -y make gcc
```

  - For RHEL 8.x

```
$ sudo dnf install -y libtdx-attest libtdx-attest-devel
$ sudo dnf install -y make gcc
```

2. Build quote generation sample

```
$ cd /opt/intel/tdx-quote-generation-sample/
$ make clean
$ make
```

3. Use test_tdx_attest to generate a quote.dat.

```
$ sudo chmod +x test_tdx_attest
$ sudo ./test_tdx_attest
```

4.3.6 Verify Quote on Host

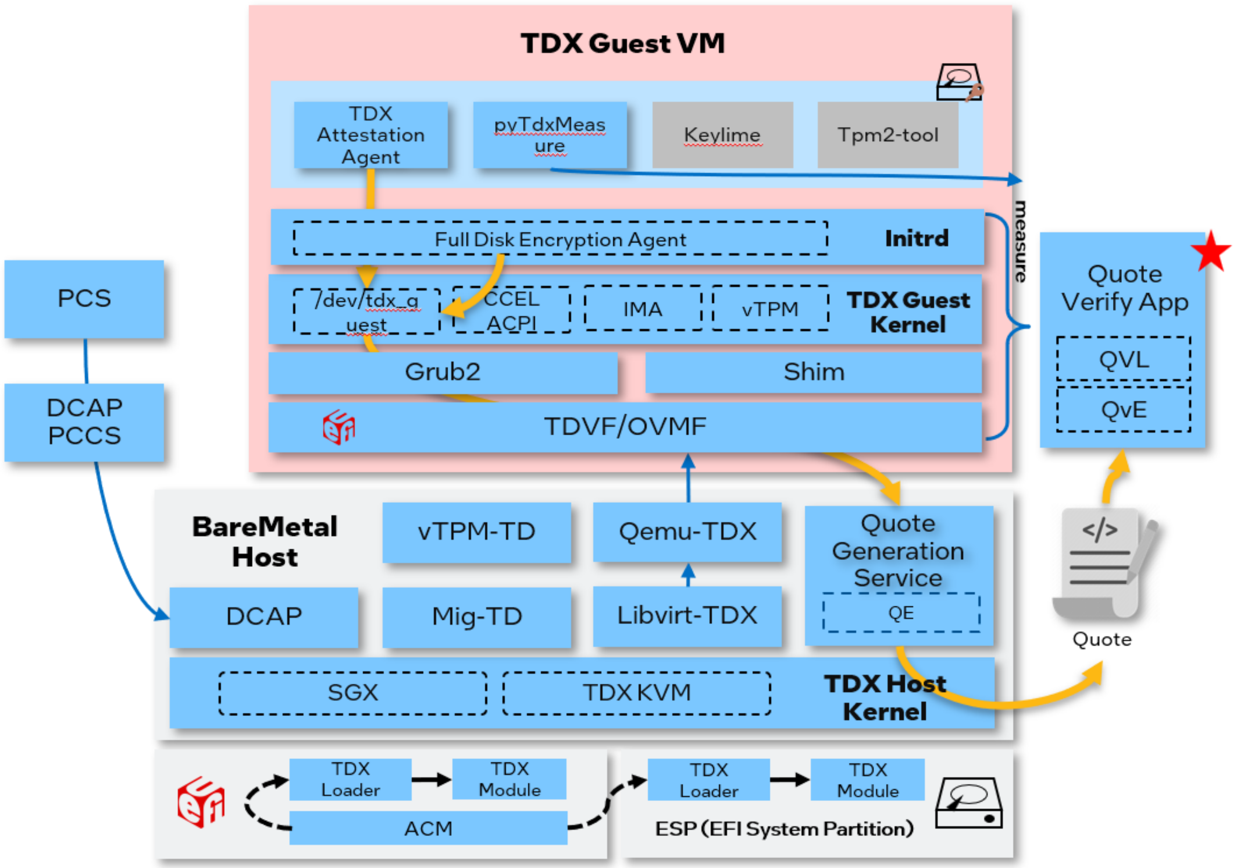


Figure 32: Verify Quote

After the Quote is generated, you can use a sample Quote verification application to verify the Quote.

1. Install the Quote verification libraries:
   - For Ubuntu 22.04

```
$ sudo apt install -y libsgx-dcap-quote-verify
$ sudo apt install -y libsgx-dcap-quote-verify-dev
```

   - For RHEL 8.x

```
$ sudo dnf install -y libsgx-dcap-quote-verify
$ sudo dnf install -y libsgx-dcap-quote-verify-devel
```

2. Copy quote.dat from TDVM

   Use `scp` or `virt_copy_out` to copy the quote from the TDVM.

```
$ # use scp to copy the quote from TDVM to host
$ scp <TDVM-user>@<TDVM-IP>:<path-to>/quote.dat <host_directory>/.
$ # use virt-copy-out to copy the quote from TDVM to host
$ sudo virt-copy-out -a <image_name> <directory_in_TDVM_contains_quote.dat>
<host_directory>
```

NOTE: Terminate the TDVM before using `virt_copy_out` *to copy out the quote.dat.*

3. Build and run sample application verifying the generated quote:

```
$ git clone https://github.com/intel/SGXDataCenterAttestationPrimitives.git
$ cd SGXDataCenterAttestationPrimitives/SampleCode/QuoteVerificationSample
$ make SGX_DEBUG=1
$ ./app -quote <PATH>/quote.dat
```

5 TD Migration

5.1 Overview

VM migration is an action of moving VM from one resource to another, such as from one host to another host to achieve the goal of improving resource utilization or keeping VM running when original host needs to bring down for maintenance purpose.

TD migration solution helps Cloud service providers to relocate/migrate an executing TD guest from a source TDX platform to a target TDX platform. A TD guest runs in a CPU mode that protects the confidentiality of its memory and CPU state from another other platform software, including host VMM. The primary security objective must be maintained while allowing TD resource manager (host VMM) to migrate TD guest across compatible platforms.

The following diagram illustrates TD migration architecture.

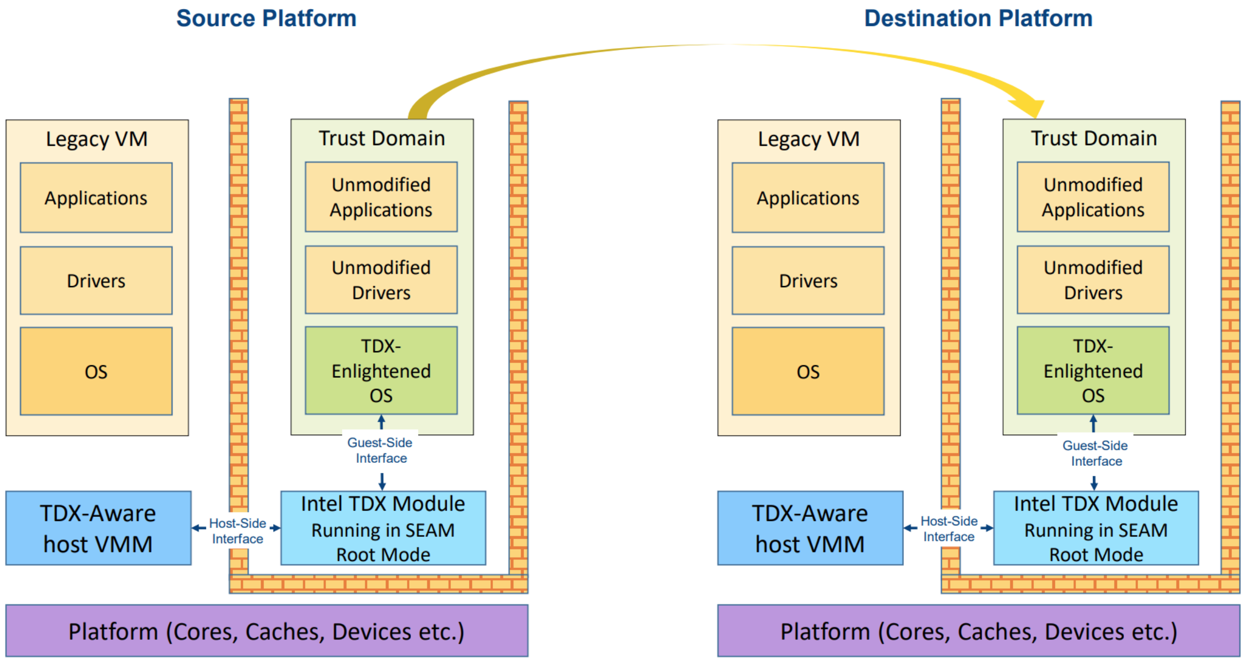


Figure 33: TD migration

In this section. the TD that will be migrated is called source TD. The TD of migration destination is called destination TD. A new component Migration TD (aka MigTD) is introduced as assistance of TD migration. It will perform functions of evaluating migration policy and transfer Migration Session Key (MSK) for TD migration.

A MigTD should be bound to source TD and destination TD before migration can start. A MigTD can be bound to more than one TD guest.

The TD migration process can be divided into 2 parts - Pre-migration and Migration.

- Pre-migration: MigTD will evaluate migration source and destination to adherence to TD migration policy. After that, MSK will be generated and transferred to destination host.
- Migration: TD content will be transferred to destination platform and the TD content will be protected by MSK.

The following diagram illustrates TD migration flow.

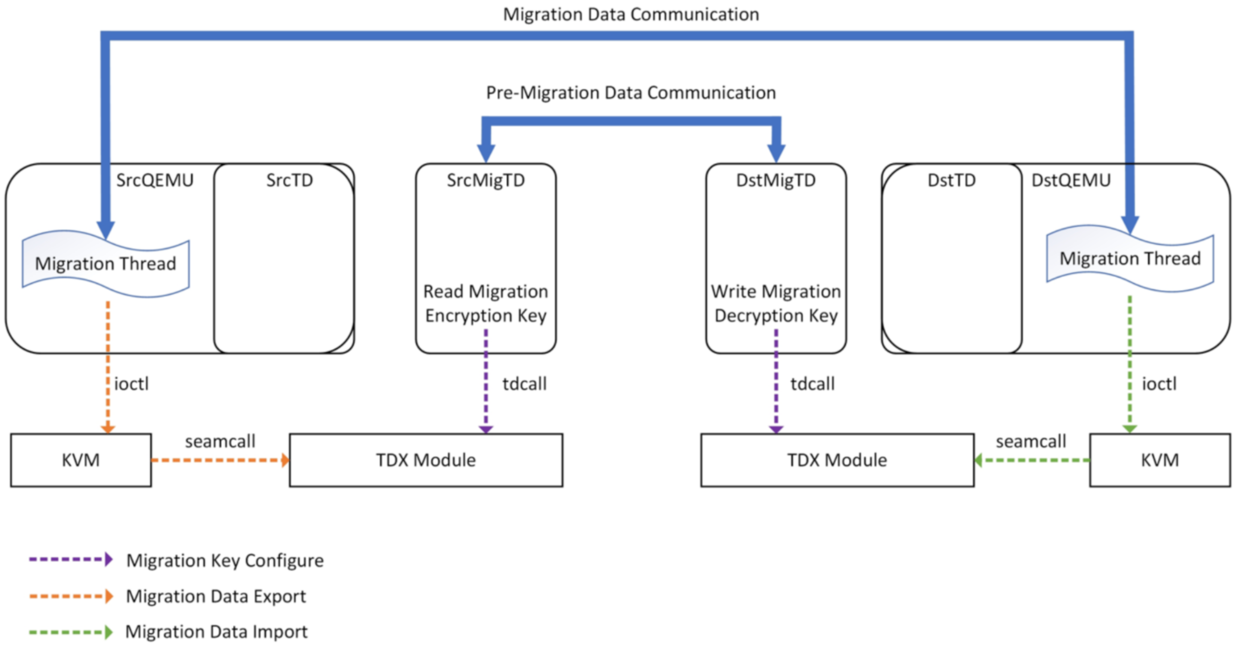


Figure 34: TD migration communication flow

5.2 Prerequisite

Pre-migration phase involves MigTD's attestation, so it requires to setup Quote generation service (QGS) and PCCS before running pre-migration. Please refer to 4.3 Attestation

Install TDX migration package using below commands.

For Ubuntu 22.04 host:

```
$ sudo apt-get install td-migration
```

For RHEL 8.* host:

```
$ sudo dnf install intel-mvp-tdx-migration
```

5.3 TD migration guide

The following sections introduce how to perform TD migration either using TDX QEMU or TDX Libvirt.

5.3.1 TD migration using QEMU

TD migration is mainly supported via TDX Qemu. In this section, the scripts are using Qemu commands to go through TD migration steps.

The scripts are under the directory `utils/td-migration/` of tdx-tools. The overall steps will be like below.

- Create MigTD on source and destination (`mig-td.sh`)
- Create user TD on source and destination (`user-td.sh`)
- Pre-migration (`connect.sh, pre-mig.sh`)
- Live migration (`mig-flow.sh`)

Please check details in the following sections.

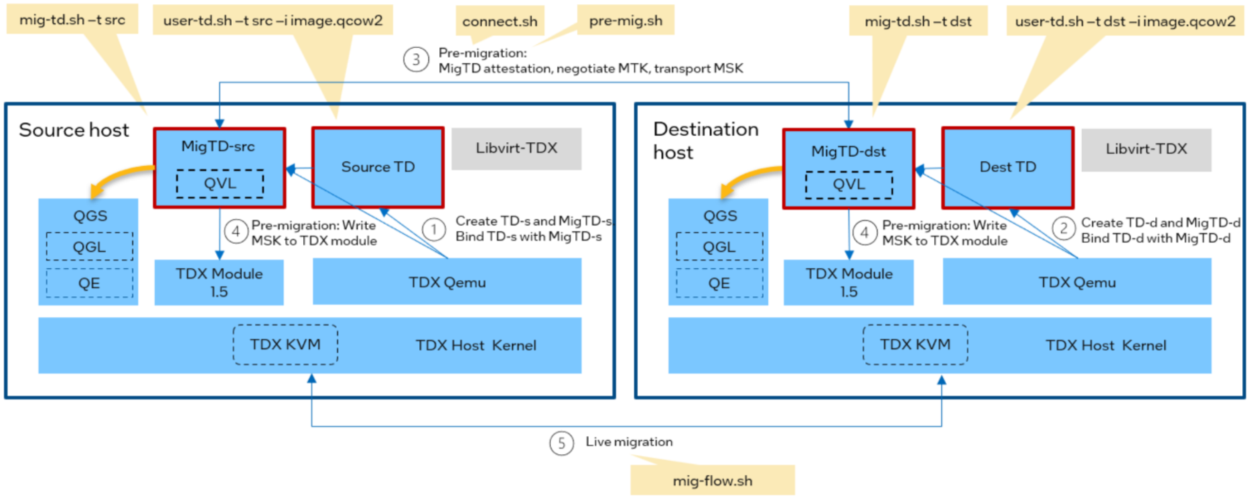


Figure 35: TD migration workflow

5.3.1.1 Pre-copy migration

Pre-copy is the most used type of VM live migration. The source VM memory content copy starts and keeps transferring until meeting a stopping condition. Then the VM stops at the source host and be initiated at the destination host. TD migration via pre-copy can be triggered either using TDX QEMU or using TDX Libvirt. It shows how to run pre-copy migration via QEMU in this section.

NOTE: Each command needs one terminal, so please prepare 5 terminals or use tmux.

```
# Single Host Migration guide

# 1. Create MigTD_src to bind with source user TD
$ sudo ./mig-td.sh -t src
# 2. Create MigTD_dst to bind with destination user TD
$ sudo ./mig-td.sh -t dst

# If MigTD starts successfully, the console will display the below message.
MigTD Version - 0.2.2
Loop to wait for request

# You can check whether the 2 MigTD are created successfully by checking qemu
process. It's supposed to show 2 qemu processes for the 2 MigTD.
$ sudo ps -ef | grep qemu | grep migtd

# 3. Launch source TD and destination TD via direct boot or grub boot. Source TD
will boot to console successfully. A qemu process will be started for destination
TD but nothing will display in console until migration completes.

# Direct Boot
$ sudo ./user-td.sh -t src -i <path/to>/image -k <path/to>/kernel
$ sudo ./user-td.sh -t dst -i <path/to>/image -k <path/to>/kernel

# Grub Boot
$ sudo ./user-td.sh -t src -i <path/to>/image -b grub
$ sudo ./user-td.sh -t dst -i <path/to>/image -b grub

# If you want to run attestation for userTD, it needs to boot TD with vsock or
tdvmcall.
# Boot TD and set get quote method as vsock.
sudo ./user-td.sh -t src -i <path/to>/image -b grub -q vsock

# Boot TD and set get quote method as tdvmcall.
sudo ./user-td.sh -t src -i <path/to>/image -b grub -q tdvmcall

# 4. Pre-Migration
# Create a channel for MigTD_src and MigTD_dst.
$ sudo ./connect.sh
# Check there are 2 socat process running
$ ps axu| grep socat

# 5. Start Pre-Migration
```

```
$ sudo ./pre-mig.sh

# Check if pre-migration is successful in dmesg output. There should be 2 messages
about pre-migration is done.
$ dmesg
[110722.032798] kvm_intel: Pre-migration is done, userspace pid=368587
[110722.074132] kvm_intel: Pre-migration is done, userspace pid=368515

# 6. Start Migration
$ sudo ./mig-flow.sh

# You can check migration status by running the following command in Qemu monitor
of source TD.
(qemu) info migrate
…
Migration status: active
total time: 147699 ms
expected downtime: 300 ms
setup: 11 ms
transferred ram: 3345444 kbytes
throughput: 936.92 mbps
remaining ram: 13496592 kbytes
total ram: 16781448 kbytes
…

# After migration is complete, you can see the following message. Destination TD
will be ready in the terminal of booting destination TD.

$ dmesg
[110983.886989] migration flow is done, userspace pid 397008
```

```
# Cross Host Migration guide

NOTE:
Guest image of source TD should be accessible from destination platform. In this
section, it uses NFS for guest image sharing.
Source host and destination host should have the same BIOS version and use the
same Linux TDX SW stack.

# 1. Create MigTD on both source and destination host

# Run the following command on source host. It will create a MigTD for source TD.
$ sudo ./mig-td.sh -t src

# Run the following command on destination host. It will create a MigTD for
destination TD.
$ sudo ./mig-td.sh -t dst

# 2. Create source TD and destination TD via direct oot or grub boot

# Direct Boot
# create the source user TD on source host
$ sudo ./user-td.sh -t src -i <path/to>/image -k <path/to>/kernel
```

```
# create the destination user TD on dest host. A qemu process will be started for
destination TD after running user-td.sh but nothing will display in console until
migration completes.
$ sudo ./user-td.sh -t dst -i <path/to>/image -k <path/to>/kernel

# Grub Boot
# create the source user TD on source host
$ sudo ./user-td.sh -t src -i <path/to>/image -b grub

# create the destination user TD on dest host
$ sudo ./user-td.sh -t dst -i <path/to>/image -b grub

# 3. Create socat channel
# This step has a little difference with the single host live migration.
# Create a channel for MigTD_src and MigTD_dst. Run this command on source
platform.
$ sudo ./connect.sh -t remote -i <DEST_HOST_IP>

# 4. Start Pre-Migration on source host
$ sudo ./pre-mig.sh -t remote -i <DEST_HOST_IP>

# Check whether pre-migration is successful on both source and destination hosts.
It's expected to see a message similar as the follows.

$ dmesg
[110722.032798] kvm_intel: Pre-migration is done, userspace pid=368587

# 5. Start Migration on source host
$ sudo ./mig-flow.sh -i <DEST_HOST_IP>

# You can check migration progress by running the following command in Qemu
monitor of source TD. When it completes, the status will be completed. The example
output is as follows.

(qemu) info migrate
…
Migration status: completed
total time: 14699 ms
expected downtime: 300 ms
setup: 11 ms
…

# After migration is complete, you can see the following message on destination
platform. Destination TD will be ready in the terminal of booting destination TD.

$ dmesg
[110983.886989] migration flow is done, userspace pid 397008
```

5.3.1.2 Cancel migration

Migration can be cancelled in case users want to abort migration or the connection between source and destination TD is interrupted. After migration is cancelled, source TD will not be affected and still works well.

```
# If you want to abort TD migration, please connect to Qemu monitor and run the
following command.

(qemu) migrate_cancel
```

If you want to re-migrate the source TD, please refer to 5.3.1.1 Pre-copy migration to go through migration process again and make sure:

- Destination TD has been created.
- Re-run pre-migration and it passed.
- Trigger migration.

5.3.1.3 Post-copy migration

Post-copy migration is another type of VM live migration. It defers the transfer of a VM's memory contents until after its processor state has been sent to the target host. This strategy can provide a "winwin" by reducing total migration time while maintaining the liveness of the VM during migration.

For TD post-copy migration, it shares the same steps of starting migTD, starting source TD and destination TD, pre-migration as pre-copy does. Please refer to 5.3.1.1 Pre-copy migration to start migTD, user TD and complete pre-migration. The only difference is in the step of migration. Please run below command to trigger post-copy migration.

NOTE: It doesn't support to enable post-copy and multi-stream at the same time.

```
# Start Migration
$ sudo ./mig-flow.sh -c

# Check migration status and you can see it's postcopy-active
(qemu) info migrate
…
Migration status: postcopy-active
…
```

5.3.1.4 Multi-stream migration

Multi-stream migration supports to enable multi-FD for TD migrations, which allows multiple parallel connections in one migration, and utilize more network capacity.

For TD multi-stream migration, it shares the same steps of starting migTD, starting source TD and destination TD, pre-migration as pre-copy does. Please refer to 5.3.1.1 Pre-copy migration to start migTD, user TD and complete pre-migration. The only difference is in the step of migration. Please run below command to trigger multi-stream migration.

NOTE: It doesn't support to enable post-copy and multi-stream at the same time.

```
# Start Migration enabling multifd and set multifd_channel number to 4
$ sudo ./mig-flow.sh -m -n 4

# Check migration parameters and you can see multifd_channel number
(qemu) info migrate_parameters
```

5.3.1.5 Pre-binding

Pre-binding supports to bind a user TD to a migTD with migTD hash in case migTD is not created yet. It doesn't require migTD to be ready before user TD. The migTD hash is calculated based on migTD binary and a fixed TD configuration (TD Attributes and XFAM, etc.). It will be generated along with migTD build. The hash file will be generated under the same directory of `migtd.bin`. By default, it's at `/usr/share/td-migration/`. The hash of migTD has been calculated and stored in `/usr/share/td-migration/migtd.servtd_info_hash`. The hash needs to be used as input of "-v" when running below script. The real binding needs to be done before pre-migration. Please run below command to go through migration using pre-binding.

```
# 1. Create source migTD and destination migTD, please refer to steps of Pre-copy
Migration

# 2. Boot source TD and destination TD using migTD hash other than migTD PID. "-v"
indicates
$ sudo ./user-td.sh -t src -i <path/to>/image -b grub -g -v <migtd_hash>
$ sudo ./user-td.sh -t dst -i <path/to>/image -b grub -g -v <migtd_hash>

# create migTD
$ sudo ./mig-td.sh -t src
$ sudo ./mig-td.sh -t dst

# 3. Pre-migration
$ sudo ./connect.sh
# Bind migTD PID to user TD before pre-migration starts
$ sudo ./pre-mig.sh -b

# 4. Migration
$ sudo ./mig-flow.sh
```

5.3.2 TD migration using Libvirt

TDX Libvirt also supports TD pre-copy migration. Users need to create migTD and provide migTD pidfile in Libvirt XML template for TD. Then TD migration can be triggered the same way as traditional VM migration.

It doesn’t support below features via TDX Libvirt yet.

- TD post-copy migration
- TD multi-stream migration
- MigTD pre-binding

5.3.2.1 Prerequisite

As mentioned in the previous section, the binary tool “socat” is also used in the TDX Libvirt to establish a channel to verify two TD guests. Therefore, the “socat” need to be installed in the source host and destination host before.

And the migTD need to be launched manually. The command below is an example.

```
# 1. Create MigTD_src to bind with source user TD
$ sudo tdx-tools/utils/td-migration/mig-td.sh -t src
# 2. Create MigTD_dst to bind with destination user TD
$ sudo tdx-tools/utils/td-migration /mig-td.sh -t dst
```

The migtTD will provide a pidfile to expose its pid to the TDX Libvirt. The script in this release will create files “`/var/run/migtd-src.pid`” and “`/var/run/migtd-dst.pid`” for the migTDs on the source host and the destination respectively.

5.3.2.2 TD launch and migration

The definition xml file describes a TD. To create a migratable TD, the policy of launch security should disable the debug flag, the value of which is “0x10000000”. Besides, the new entry <migration> should be added to the definition file, being the direct child of the domain entry. The definition file can be formed in the following example.

```
<domain type='kvm' …>
    …
  <launchSecurity type='tdx'>
    <policy>0x10000000</policy>
    <Quote-Generation-Service>vsock:2:4050</Quote-Generation-Service>
  </launchSecurity>
  <migration>
<migtd>
  <srcPidFile>/var/run/migtd-src.pid</srcPidFile>
  <dstPidFile>/var/run/migtd-dst.pid</dstPidFile>
```

```
</migtd>
  </migration>
</domain>
```

The <srcPidFile> points to the migTD pidfile on the source host and the <dstPidFile> points to the migTD pidfile on the destination host. The migration command for TD is the same as traditional VM, except that current TDX Libvirt only support simple live migration. On the source host, run the below command to trigger migration.

```
$ virsh migrate --live qemu+ssh://[dst-host-name]/system
```

The speed of live migration can be affected by the memory size of the guest and the bandwidth of the network between two hosts.

5.4 Reference

Pre-migration will do migration policy checking. TD migration can only be performed after pre-migration is successful. The following error code is for you reference in case pre-migration fails.

Table 8: Pre-migration result code

Code	Description
0	SUCCESS
1	INVALID_PARAMETER
2	UNSUPPORTED
3	OUT_OF_RESOURCE
4	TDX_MODULE_ERROR
5	NETWORK_ERROR
6	SECURE_SESSION_ERROR
7	MUTUAL_ATTESTATION_ERROR
8	MIGPOLICY_ERROR
0xFF	MIGTD_INTERNAL_ERROR

The default migration policy will check the following items and only pass when the policy is met on source and destination platform. Please check policy details in the following table.

Table 9: Pre-migration policy

Field	Policy item	Operation
TEE_TCB_INFO	TEE_TCB_SVN.SEAM	greater or equal
TEE_TCB_INFO	MRSEAM	equal
TEE_TCB_INFO	MRSIGNERSEAM	equal
TEE_TCB_INFO	ATTRIBUTES	equal

TDINFO	ATTRIBUTES	equal
TDINFO	XFAM	equal
TDINFO	MRCONFIGID	equal
TDINFO	MROWNER	equal
TDINFO	MROWNERCONFIG	equal
EventLog	Digest.MigTdCore	equal
EventLog	Digest.MigTdPolicy	equal
EventLog	Digest.MigTdSgxRootKey	equal

6 TD Preserving

The TDX module is designed to be able to reload the new one with TD guests and legacy guests running, without rebooting the host.

NOTE: Currently, given TDX module has no production-signed version yet, it only supports reloading the same one that is running on the host.

6.1 Prepare new TDX module

Make sure you have the following files. They represent new TDX module. This new TDX module will be loaded during TD Preserving.

```
/lib/firmware/intel-seam/libtdx.bin
/lib/firmware/intel-seam/libtdx.bin.sigstruct
```

6.2 Trigger TD Preserving

Trigger TD Preserving via the following command.

```
$ echo update > /sys/devices/system/cpu/tdx/reload
```

Wait for a few seconds and check dmesg. It should display “tdx: TDX module initialized” and you can see version information of new TDX module. The following is a part of example output. TDX module version could vary.

```
[   26.183842] tdx: TDX module: atributes 0x80000000, vendor_id 0x8086,
major_version 1, minor_version 5, build_date 20230525, build_num 534
[   26.184252] tdx: TDX module: features0: fbf
[   26.707902] tdx: 131331 pages allocated for PAMT.
[   26.713246] tdx: TDX module initialized.
```

7 vTPM

vTPM for TDX solution provides TPM 2.0 compliant device to TD guest. A TD with vTPM device can work with tpm2-tools, IMA and Keylime to utilize TPM functionality, TPM PCR and Keylime attestation process.

Two specific components are introduced to enable vTPM for TD:

- A vTPM TD to support vTPM functionality.
- A new TDVF with vTPM enabled.

Note that vTPM solution is supported since TDX 1.5 stack 2023WW27.

7.1 Installation

Install vTPM TD and vTPM TDVF on Ubuntu 22.04

```
$ sudo apt install -y vtpm-td ovmf
```

Install vTPM TD and vTPM TDVF on RHEL 8.x

```
$ sudo dnf install -y intel-mvp-vtpm-td intel-mvp-ovmf
```

If you are using 2023WW27 release, check whether vTPM TD and vTPM OVMF have been installed.

```
$ # vTPM TD
$ ls /usr/share/tdx-vtpm/vtpmtd.bin
$ # vTPM OVMF
$ ls /usr/share/tdx-vtpm/OVMF.fd
```

7.2 Launch TD with vTPM enabled

Please refer to https://github.com/intel/tdx-tools to get TD base Libvirt xml template and rename it to `tdx_libvirt_direct.xml`.

1. Update OVMF path

- If using 2023WW27 release, please add `/usr/share/tdx-vtpm/OVMF.fd` in `<os>-<loader>` section.

2. Add vTPM template element <vtpm> as follows.

`<loader>` is required for vTPM, it should be configured to vTPM TD's binary. `<log>` is optional in case to capture vTPM's running log.

```
<domain type='kvm' xmlns:qemu='http://TDX Libvirt.org/schemas/domain/qemu/1.0'>
...
<os>
  ...
  <loader>/usr/share/tdx-vtpm/OVMF.fd</loader>
  ...
</os>
...
<launchSecurity type='tdx'>
    ...
    <vtpm>
      <loader>/usr/share/tdx-vtpm/vtpmtd.bin</loader>
      <log>/tmp/vtpm-td.log</log>
    </vtpm>
 </launchSecurity>
...
</domain>
```

To launch a TD with vTPM enabled, it is same as normal TD.

```
$ virsh create tdx_libvirt_direct.xml
```

7.3 Verify vTPM features

After booting up to TD guest OS, vTPM features can be used as normal TPM. tpm2-tools can be used to verify vTPM features. It's recommended to build and install `tpm2-tools` in TD guest image.

Please install the following dependencies before building and installing tpm2-tools.

```
$ sudo apt-get -y install autoconf-archive libcmocka0 libcmocka-dev procps
iproute2 build-essential git pkg-config gcc libtool automake libssl-dev uthash-dev
autoconf doxygen libjson-c-dev libini-config-dev libcurl4-openssl-dev uuid-dev
libltdl-dev libusb-1.0-0-dev libarchive-dev clang  libglib2.0-dev
```

Follow document: https://tpm2-tools.readthedocs.io/en/latest/INSTALL/ to build and install `tpm2-tools`.

Run tpm2_pcrread to read the PCR registers.

```
$ # Read TPM PCR register
$ tpm2_pcrread
  sha256:
    0 : 0x6EEB7D7776BD6917F9595F6AC643EA7102861ED2E6204BB16E5ED5FE8DF19435
    1 : 0xAD2E8C8588627F7DEF8340ED8B3D459D25FD42D67BC54E8A3161345C7EC9FCC2
    2 : 0x3D458CFE55CC03EA1F443F1562BEEC8DF51C75E14A9FCF9A7234A13F198E7969
    3 : 0x3D458CFE55CC03EA1F443F1562BEEC8DF51C75E14A9FCF9A7234A13F198E7969
    4 : 0x6FE4C4AA1593841114E77CE3ED2EDA2CB07796EA42E46281068406D41EF1EEA8
    5 : 0xA5CEB755D043F32431D63E39F5161464620A3437280494B5850DC1B47CC074E0
    6 : 0x3D458CFE55CC03EA1F443F1562BEEC8DF51C75E14A9FCF9A7234A13F198E7969
    7 : 0xB5710BF57D25623E4019027DA116821FA99F5C81E9E38B87671CC574F9281439
    8 : 0x0000000000000000000000000000000000000000000000000000000000000000
    9 : 0xE0C40B1D01B7EB88BD00FE4D465E38B86846C59E9C441274125DAFF7ACC2CA1A
    10: 0x93E94F77D78CF172D93E99E1F44769F7FB20990C3F02052F917A0CBA163A363D
    11: 0x0000000000000000000000000000000000000000000000000000000000000000
    12: 0x0000000000000000000000000000000000000000000000000000000000000000
    13: 0x0000000000000000000000000000000000000000000000000000000000000000
    14: 0x0000000000000000000000000000000000000000000000000000000000000000
    15: 0x0000000000000000000000000000000000000000000000000000000000000000
    16: 0x0000000000000000000000000000000000000000000000000000000000000000
    17: 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
    18: 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
    19: 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
    20: 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
    21: 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
    22: 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
    23: 0x0000000000000000000000000000000000000000000000000000000000000000
```

7.4 Keylime Attestation

Keylime is an open-source scalable trust system harnessing TPM Technology. It provides a flexible framework for the remote attestation of any given PCR. In this section, it will introduce a typical Keylime use scenario – remote attestation with TPM.

vTPM can be used for Keylime to do remote attestation with Linux IMA enabled. Keylime verifier will do continually remote attestation with Linux IMA measurement records protected with vTPM from Keylime agent deployed inside TDVM and compare against know good values provided by trusted admin or third parties.

7.4.1 Keylime Installation

Install Keylime verifier, Keylime registrar and Keylime agent:

```
$ useradd keylime -g tss
$ git clone https://github.com/keylime/keylime.git
$ cd keylime
$ ./installer.sh
```

Keylime agent is rust based, please follow https://www.rust-lang.org/tools/install to install rust runtime. Keylime agent depends on tpm2-tss and tpm2-tools to be installed as perquisitions, please follow 2.9.3 to install.

```
$ git clone https://github.com/keylime/rust-keylime.git
$ cd rust-keylime
$ cargo build --release
$ cp target/release/keylime_agent /usr/local/bin/
```

7.4.2 Configuration

Update TD Libvirt xml template adding following parameter to enable Linux IMA:

```
<cmdline>... ima_policy=critical_data</cmdline>
```

When boot with this command line option, the Linux IMA measurement records can be found at `/sys/kernel/security/ima/ascii_runtime_measurements`:

```
10 beab1f23c09f6458e298b123c8f8a647559ce772 ima-ng
sha256:6754a6b5ef16e241674dd59c8ff99964b075d9d8b87a767bc3e144b2fc508676
boot_aggregate
10 897bd9521b5e83ccc0aea36b3530e1deb5cb6f91 ima-buf
sha256:fefe31aa320223a0ba73eb5e28a05ee7fd9a459a1f7e26c4240b0998d51b7d43
kernel_version 362e322e31362d6d7670333076332b372d67656e65726963
```

Generate a Keylime runtime policy file using the IMA measurement records:

```
$ keylime_create_policy -b -m /sys/kernel/security/ima/ascii_runtime_measurements
-o runtime_policy.json
```

The generated policy file runtime_policy.json as bellow:

```
{"meta": {"version": 1, "generator": 1}, "release": 0, "digests":
{"boot_aggregate":
["6754a6b5ef16e241674dd59c8ff99964b075d9d8b87a767bc3e144b2fc508676"]}, "excludes":
[], "keyrings": {}, "ima": {"ignored_keyrings": [], "log_hash_alg": "sha1",
"dm_policy": null}, "ima-buf": {"kernel_version":
["fefe31aa320223a0ba73eb5e28a05ee7fd9a459a1f7e26c4240b0998d51b7d43"]},
"verification-keys": ""}
```

Prepare a payload file payload.txt for tenant command be used when registering agent to verifier:

```
$ echo "12345678" >  payload.txt
```

Change configure files in `/etc/keylime` to make sure it uses same hash algorithm as Linux IMA does:

```
tpm_hash_alg = "sha256" #agent.conf
transparency_log_sign_algo = sha256 #registrar.conf
transparency_log_sign_algo = sha256 #verifier.conf
```

Change configure `/etc/keylime/tenant.conf` for to ask tenant to use self-signed EK certificate.

```
require_ek_cert = False
```

Make sure `/var/lib/keylime` and all sub directories have owner run_as "keylime:tss" specified in `/etc/keylime/agent.conf`, if not, please use following command to set the owner and group.

```
$ sudo chown -R keylime:tss /var/lib/keylime
```

7.4.3 Start Keylime Components

Start Keylime verifier, Keylime registrar and Keylime agent:

```
$ keylime_verifier > keylime_verifier.log 2>&1 &
$ keylime_registrar > keylime_registrar.log 2>&1 &
$ keylime_agent > keylime_agent.log 2>&1 &
```

Add Keylime agent to verifier to do continues remote attestation:

```
$ keylime_tenant -c add --uuid d432fbb3-d2f1-4a97-9ef7-75bd81c00000 -
f ./payload.txt --runtime-policy ./runtime_policy.json
```

Use following commands to check Keylime system status:

```
$ keylime_tenant -c reglist
$ keylime_tenant -c cvstatus
$ keylime_tenant -c regstatus
```

Use following command to remove the agent from verifier:

```
$ keylime_tenant -c delete -u d432fbb3-d2f1-4a97-9ef7-75bd81c00000
```

8 Full Disk Encryption

FDE (Full disk encryption) is a security method for protecting sensitive data by encrypting all data on a disk partition. In non-confidential VM, FDE is using LUKS (Linux Unified Key Setup) with a user input disk encryption key. In confidential environments like Intel TDX, to achieve zero trust, the encryption key should be retrieved from the replying party via remote attestation.

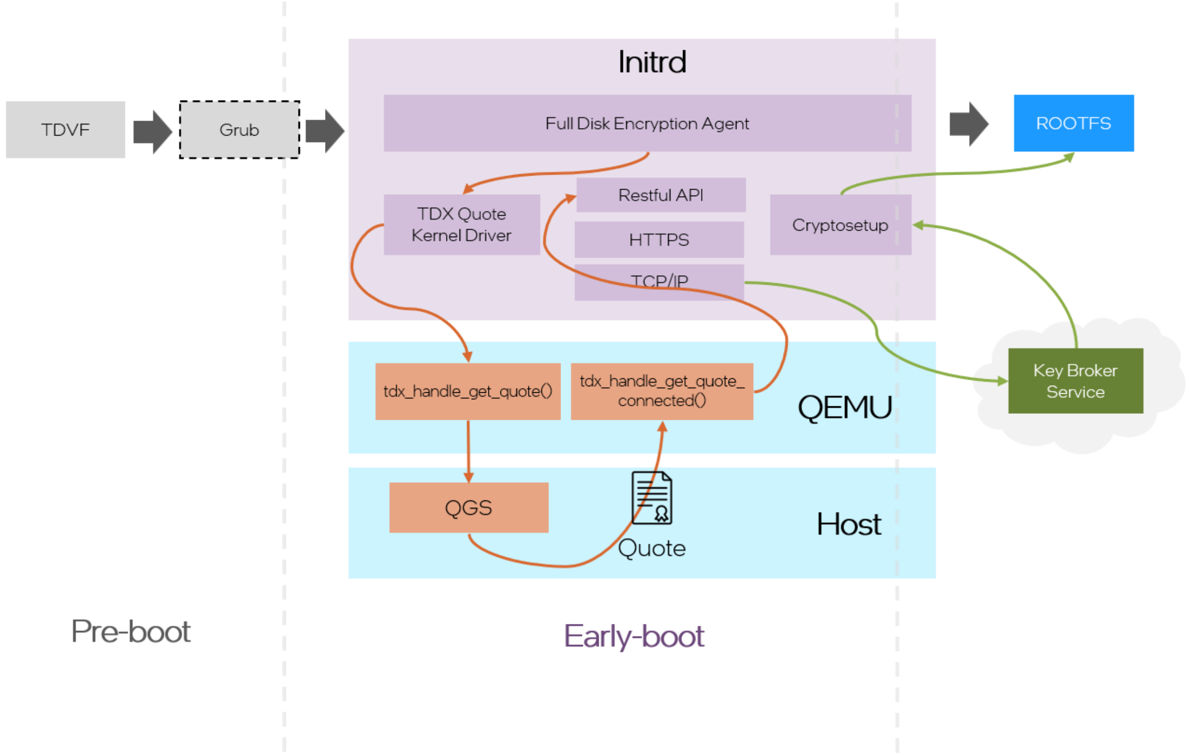


Figure 36: Full Disk Encryption in TDX Guest

The FDE can be done in OVMF at the pre-boot stage or initrd at the Linux early boot stage like. To learn more refer to the presentation "Secure Bootloader for Confidential Computing".

8.1 Workflow

This section introduces a solution/implementation to integrate FDE with Intel TDX. The workflow can be divided into 5 steps.

1. Register key and keyid from the Key Broker Service (KBS).

2. Create an encrypted guest image with the key retrieved in Step 1.
3. Install FDE components in the encrypted guest image.
4. Enroll necessary variables into OVMF.
5. Launch a TDX guest based on the encrypted guest image and the OVMF.

In the above step 1, the key and keyid pair should be registered in the KBS. Typically, the key will be used to encrypt the guest image, and the keyid is the identifier of the key in the KBS, which will be used in the decryption process. Given that KBS providers have different designs for their keys and keyids, it is recommended to register the pair of the key and the keyid after consulting the KBS provider.

In the above step 2, it creates an encrypted guest image.

In the above step 3, FDE components will be installed in the encrypted guest image. The tdx-tools provides an integrated script "`tdx-tools/attestation/full-disk-encryption/tools/image/fde-image.sh`" to complete the task. The key and the keyid is retrieved in Step 1, and the tdx-repo is built from the tdx-tools.

```
$ cd attestation/full-disk-encryption/tools/image
$ ./fde-image.sh -k ${key} -i ${keyid} -d ${tdx-repo}
```

In Step 4, several variables are enrolled in the OVMF. These variables, such as keyid, are retrieved by the fde-agent from the OVMF to help remote attestation retrieve the key from the KBS. For example, assume that the keyid is saved in a JSON file. The python script "`tdx-tools/attestation/full-disk-encryption/tools/image/enroll_vars.py`" helps enroll the data.

```
$ cd attestation/full-disk-encryption/tools/image
$ # Enroll user data
$ cat userdata.txt
{
    "keyid":"sth"
}
$ NAME="KBSUserData"
$ GUID="732284dd-70c4-472a-aa45-1ffda02caf74"
$ DATA="userdata.txt"
$ python3 tools/image/enroll_vars.py -i OVMF.fd -o OVMF.fd -n $NAME -g $GUID -d
$DATA
$ # Enroll KBS URL
$ NAME="KBSURL"
$ GUID="0d9b4a60-e0bf-4a66-b9b1-db1b98f87770"
$ DATA="url.txt"
$ python3 tools/image/enroll_vars.py -i OVMF.fd -o OVMF.fd -n $NAME -g $GUID -d
$DATA
$ # Enroll KBS Certificate
$ NAME="KBSCert"
$ GUID="d2bf05a0-f7f8-41b6-b0ff-ad1a31c34d37"
$ DATA="cert.cer"
$ python3 tools/image/enroll_vars.py -i OVMF.fd -o OVMF.fd -n $NAME -g $GUID -d
$DATA
```

In Step 5, a TDX guest is launched from the encrypted guest image. The script “tdx-tools/start-qemu.sh” can launch it. Please use the encrypted guest image and OVMF mentioned in step 3 and step 4.

```
$ OVMF_PATH=/path/to/OVMF
$ IMAGE_PATH=/path/to/image
$ start-qemu.sh \
    -b grub \
    -q tdvmcall \
    -o ${OVMF_PATH} \
    -i ${IMAGE_PATH}
```

The detailed steps are described in `tdx-tools/doc/full_disk_encryption.md`.

8.2 Prepare Encryption Image

It is complicated to create an encrypted guest image in Step 2 and Step 3. In Step 2, an empty image is created first. The image will be partitioned into several volumes, and the root filesystem partition is encrypted with the key in actual. The rootfs is then copied to the root filesystem partition.

In the Step 3, a binary named by the fde-agent and its related configuration need to be installed into the initrd. The parameter “cryptdevice=${root-enc}”, which specifies the encrypted root partition, is appended in the kernel cmdline to enable the FDE.

More details are described in the `tdx-tools/attestation/full-disk-encryption/README.md`.

9 Develop and Debug

9.1 Override the Intel TDX module

Secure arbitration mode (SEAM) is an extension to the virtual machines extension (VMX) architecture to define a new VMX root operation called SEAM VMX root and a new VMX non-root operation called SEAM VMX non-root. Collectively, the SEAM VMX root and SEAM VMX non-root execution modes are called operations in SEAM. SEAM VMX root operation is designed to host a CPU-attested, software module called the Intel® Trust-Domain Extensions (Intel® TDX) module to manage virtual machine (VM) guests called Trust Domains (TD). Currently, the Intel TDX Module is the only SEAM module that the Intel P-SEAMLDR installs [1].

By default, BIOS loads the built-in version of TDX Loader and TDX module from the IFWI during the server booting. For development or upgrading purpose without re-flashing the BIOS, a debug or new version SEAMLDR and TDX module could be placed into the ESP partition. The BIOS loads the new or debug version from ESP on the next boot.

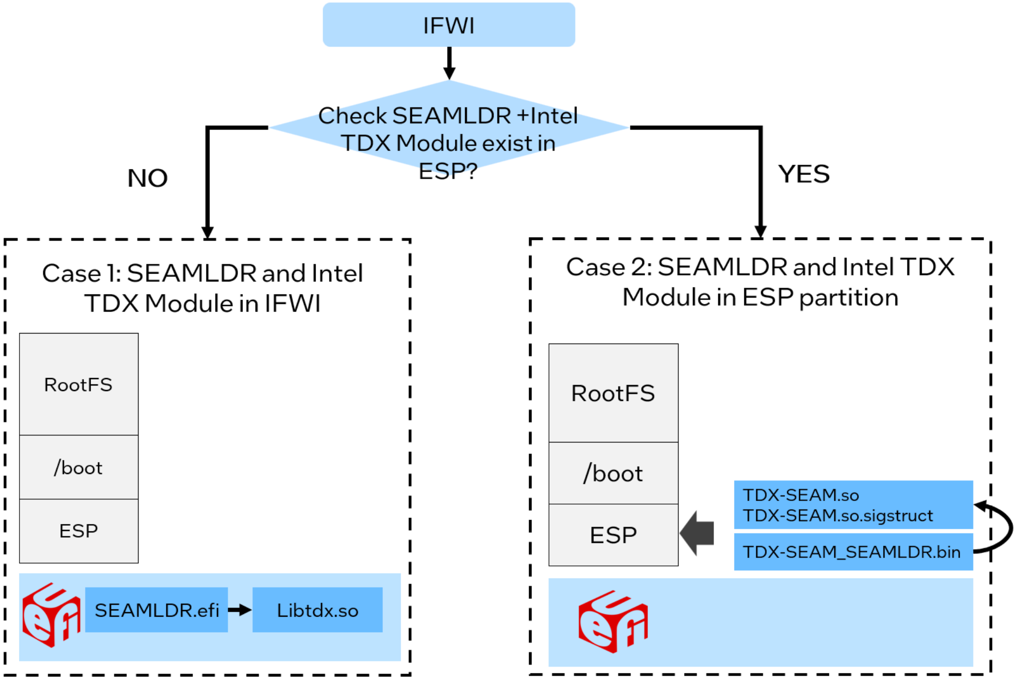

IFWI
Check SEAMLDR +Intel TDX Module exist in ESP?
NO
YES
Case 1: SEAMLDR and Intel TDX Module in IFWI
RootFS
/boot
ESP
SEAMLDR.efi
Libtdx.so
Case 2: SEAMLDR and Intel TDX Module in ESP partition
RootFS
/boot
ESP
TDX-SEAM.so
TDX-SEAM.so.sigstruct
TDX-SEAM_SEAMLDR.bin

Figure 37: BIOS Search TDX Module from ESP

The naming rule is:

- <ESP>/EFI/TDX/TDX-SEAM_SEAMLDR.bin
- <ESP>/EFI/TDX/TDX-SEAM.so
- <ESP>/EFI/TDX/TDX-SEAM.so.sigstruct

Check the updated TDX module information.

```
# It will display a string including version information of tdx module, such as
major version, monir version, build date, etc.

$ sudo cat /sys/firmware/tdx/tdx_module/*
0x00000000202302060x000001c90x000000010x00000000initialized0x00008086
```

9.2 Off-TD Debug via GDB from the Host

QEMU supports working with gdb via gdb's remote-connection facility (the "gdbstub"). This allows you to debug guest code in the same way that you might do with a low-level debug facility like JTAG on real hardware. You can stop and start the virtual machine, examine states like registers and memory, and set breakpoints and watchpoints. Refer to https://www.QEMU.org/docs/master/system/gdb.html for detailed gdb usage.

To support gdb the Intel TDX module exposes the following APIs:

- TDH.VP.RD/WR to allow QEMU emulator to read/write guest's CPU states.
- TDH.MEM.RD/WR to allow QEMU emulator to read/write guest memory.

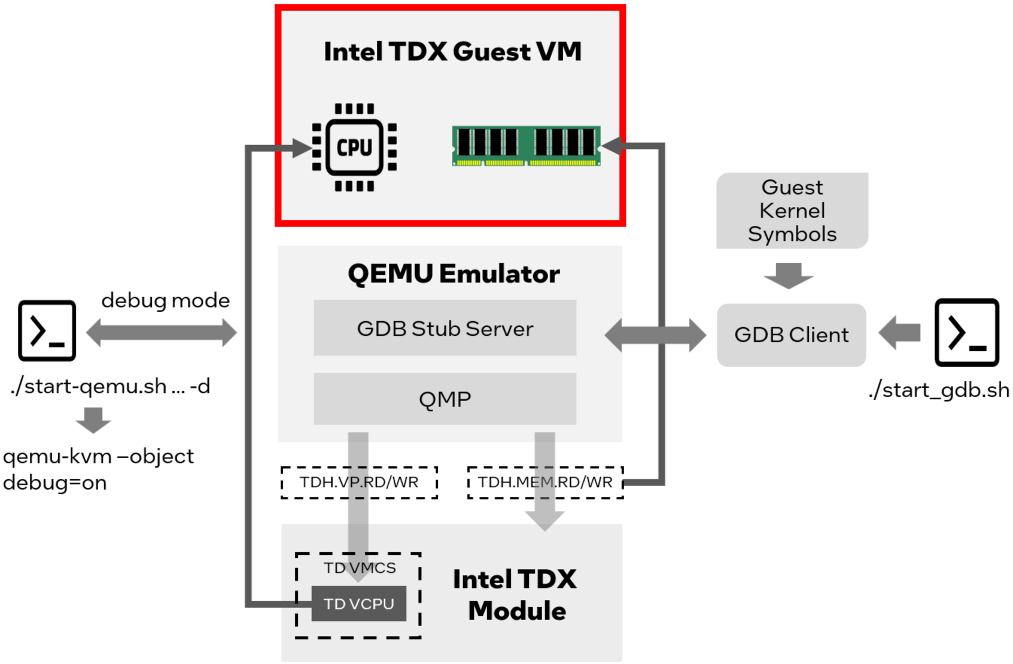


Figure 38: Off-TD Debug via GDB

Steps to debug TD guest are as follows:

- Step 1: Start TD guest in debug mode
    - Append "debug=on" to "-object". For example:

```
-object tdx-guest,id=tdx,debug=on
```

    - Add -s -S parameter to QEMU-kvm. For example:

```
$ QEMU-kvm -s -S
```

    - Disable kernel address randomization by append "nokaslr"

- If booting TD via start-qemu.sh, please refer to below command to set "debug=on":

```
$ ./start-qemu.sh -i <guest image> -k <guest kernel> -d
```

- Step 2: Install the guest kernel's debug symbol into the host.

```
$ sudo dnf install intel-mvp-tdx-guest-kernel-debuginfo
```

- Step 3: Run the script start_gdb.sh with the following content.

```
#!/bin/bash
GDB=gdb
MOD_DIR=/usr/lib/debug/usr/lib/modules/<guest kernel>/
$GDB \
-ex "add-auto-load-safe-path $MOD_DIR" \
-ex "file $MOD_DIR/vmlinux" \
-ex "set arch i386:x86-64:intel" \
-ex "set remotetimeout 360" \
-ex "target remote 127.0.0.1:1234“
```

- Step 4: In the GDB console, use command "hb" to set the first break point.

```
gdb> hb start_kernel
```

The software breakpoint is available after the kernel is loaded into Guest Physical Address (GPA) space by QEMU.

9.3 Check Memory Encryption

There are lots of approaches to check whether TDX memory is encrypted or not. This section introduces how to do this check via a GDB debug approach.

1. Install the kernel development package on the host for debug symbols (using RHEL distro as example):

```
$ sudo dnf install intel-mvp-tdx-kernel-devel
```

2. Get the GVA (guest virtual address) of the `.text` code section of guest kernel.

```
$ # Extract the guest kernel binary
$ /usr/src/kernels/$(uname -r)/scripts/extract-vmlinux <path-to-guest-kernel-
file > vmlinux
$ objdump -d vmlinux > disassembled-vmlinux.asm && head -n 20 disassembled-
vmlinux.asm
...
ffffffff81000000 <.text>:
ffffffff81000000:   48 8d 25 51 3f c0 01     lea   0x1c03f51(%rip),%rsp
ffffffff81000007:   48 8d 3d f2 ff ff ff     lea   -0xe(%rip),%rdi
ffffffff8100000e:   56                       push %rsi
ffffffff8100000f:   e8 dc 06 00 00           callq 0xffffffff810006f0
```

```
...
```

The result shows that the virtual address of `.text` section starts from `0xffffffff81000000`.

3. Verify the instructions/memory at the guest physical address of the .text code section in a non-confidential VM guest.
   - Launch a non-confidential guest, `nokaslr` should be appended for kernel command like below to turn off the Kernel Address Space Layout Randomization (KASLR).

```
-append "root=/dev/vda1 console=hvc0 nokaslr"
```

   - Enter QEMU monitor shell

     If using start-qemu.sh, just "telnet 127.0.0.1 9001"

   - Disassemble the virtual address of the .text section

```
(QEMU) stop
(QEMU) x /10i 0xffffffff81000000
0x01000000:  48 8d 25 51 3f c0 01     leaq     0x1c03f51(%rip), %rsp
0x01000007:  48 8d 3d f2 ff ff ff     leaq     -0xe(%rip), %rdi
0x0100000e:  56                       pushq    %rsi
0x0100000f:  e8 dc 06 00 00           callq    0x10006f0
```

4. Verify the instructions/memory at guest physical address of .text code section in a TD guest.
   - Launch a TD guest
     - debug=on should be appended for QEMU command line

```
-object tdx-guest,id=tdx,debug=on
```

     - `nokaslr` should be appended for kernel command line

```
-append "root=/dev/vda1 console=hvc0 nokaslr"
```

   - Enter QEMU monitor shell

     If using start-QEMU.sh, just "telnet 127.0.0.1 9001"

   - Disassemble the virtual address of .text section

```
(QEMU) stop
(QEMU) x /10i 0xffffffff81000000
0xffffffff81000000:  98                       cwtl
0xffffffff81000001:  f8                       clc
0xffffffff81000002:  49 5e                    popq     %r14
0xffffffff81000004:  5a                       popq     %rdx
0xffffffff81000005:  55                       pushq    %rbp
...
```

The disassembled instructions should be different from a non-confidential guest and should look meaningless (all zero) since the memory is encrypted.

9.4 Troubleshooting

9.4.1 Failed to boot non-TDX host kernel with TDX enabled in BIOS, hit machine check xxxxxxxx00061136

When TDX is enabled in BIOS, non-TDX host kernel may fail to boot with below message:

```
[Mca]CheckEmcaSmiError returns TRUE
[Mca]McaDetectAndHandle start
[Mca]McaDetectAndHandle, state is 0x0
[Mca]McaDetectAndHandle, state is 0x1
[Mca]ProcessSocketMcBankError: Inside the function
S0 C3 T1 [Mca]McBankErrorHandler: Skt = 0x0, McBank = 0x9, State = 0x1
S0 C3 T1 [Mca]McBankErrorHandler: Skt = 0x0, McBank = 0x9, State = 0x2
S0 C3 T1 [CpuRas]MC status 0xBE20000000061136, class FATAL
S0 C3 T1 [Mca]McBankErrorHandler: Skt = 0x0, McBank = 0x9, State = 0x4
S0 C3 T1 [CpuRas]MC status 0xBE20000000061136, class FATAL
System address:D1FFC000 is not DRAM address
ERROR: C00000002:V03071008 I0 D6476950-2481-4CBB-8400-442542C766C8 7C93FE18
```

When Trust Domain Extension (TDX) is Enabled in BIOS, the distribution-provided kernel may not boot due to `CONFIG_MTRR_SANITIZER=y` to wrongly clean MTRR entry with TDX/MKTME private bit.

To boot non-TDX distro default kernel, `disable_mtrr_cleanup` should be added to kernel command line:

- In grub menu, press "e" entering the editing mode.
- Append `disable_mtrr_cleanup` in kernel command line like:

```
BOOT_IMAGE=(hd0,gpt2)/vmlinuz-4.18.0-193.el8.x86_64 root=/dev/mapper/cl-root ro
crashkernel=1G
resume=/dev/mapper/cl-swap rd.lvm.lv=cl/root rd.lvm.lv=cl/swap console=tty0
earlyprintk=ttyS0,115200 disable_mtrr_cleanup
```

10 Virtual Machine Administrator

In this section, it assumes that TD has boot successfully by host OS administrators. It will introduce how to use TD from virtual machine administrator perspective.

10.1 Run AI Workload with Intel AMX

Intel AMX is a new built-in accelerator that improves the performance of deep-learning training and inference on the CPU. This is ideal for workloads like natural-language processing, recommendation systems, and image recognition.[10] It is available on the 4th Gen Intel® Xeon® Scalable processors.

Use the following approach to check its capability on the TD guest.

```
$ grep -o amx /proc/cpuinfo
# Expect to see output of several "amx". Empty results mean Intel AMX is not
enabled.
```

This section introduces how to run AI workload boosted by Intel AMX within an Intel TD guest. This offers another layer of security over traditional VM's to protect the model data while it is being used.

- Install the Intel® Optimization for TensorFlow* version 2.8.0 via pip. Python versions supported are 3.7, 3.8, 3.9, 3.10. For TensorFlow versions 1.13, 1.14 and 1.15 with pip > 20.0, if you get an "invalid wheel error", try to downgrade the pip version to < 20.0

```
$ dnf install python3
$ python -m pip3 install intel-tensorflow-avx512==2.8.0
```

- Download a pre-trained model.

```
$ wget https://storage.googleapis.com/intel-optimized-tensorflow/models/v1_8/
mobilenet_v1_1.0_224_frozen.pb
```

- Clone the intelai/models repo and then navigate to the benchmark directory.

```
$ dnf install git
$ git clone https://github.com/IntelAI/models.git cd models/benchmarks
```

- Intel® Optimization for TensorFlow uses Intel® oneAPI Deep Neural Network Library (oneDNN) and OpenMP library. The DNNL_MAX_CPU_ISA environment variable can be used to limit processor features for oneDNN, it should be set to AVX512_CORE_AMX to use AMX features. The

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OMP_NUM_THREADS and KMP_AFFINITY environment variables set the number of threads and thread affinity for OpenMP library. Set these environment variables.

```
$ export DNNL_MAX_CPU_ISA=AVX512_CORE_AMX
$ export OMP_NUM_THREADS=16
$ export KMP_AFFINITY=granularity=fine,verbose,compact
```

- Run online inference. Replace <PATH> to the absolute path where the pre-trained model is located.

```
$ python3 launch_benchmark.py \
--benchmark-only --framework tensorflow --model-name mobilenet_v1 \
--mode inference --precision bfloat16 --batch-size 1 \
--in-graph /opt/mobilenet_v1_1.0_224_frozen.pb \
--num-intra-threads 16 --num-inter-threads 1 --verbose --\ input_height=224
input_width=224 warmup_steps=20 steps=20 \ input_layer='input'
output_layer='MobilenetV1/Predictions/Reshape_1'
```

- The result will look like the following.

```
[Running warmup steps...]
steps = 10, 360.33539518900346 images/sec steps = 20, 349.292471685543 images/sec
[Running benchmark steps...]
steps = 10, 364.1521097412745 images/sec steps = 20, 369.8028566390407 images/sec
Average Throughput: 364.37 images/s on 20 iterations
```

If running same workload without "**export DNNL_MAX_CPU_ISA=AVX512_CORE_AMX**", the result will be a noticeably smaller (images/sec) because AMX is not being used to accelerate.

NOTE: If you fail to run above commands and see a message like "If you cannot immediately regenerate your protos, some other possible workarounds are: 1. Downgrade the protobuf package to 3.20.x or lower. 2. Set PROTOCOL_BUFFERS_PYTHON_IMPLEMENTATION=python (but this will use pure-Python parsing and will be much slower)." you have two options. Option 1 is to upgrade the protobuf version to 3.20.0 as following:

```
$ pip3.8 install --upgrade protobuf==3.20.0
```

Option 2 is to set the environment variable as following

```
$ export PROTOCOL_BUFFERS_PYTHON_IMPLEMENTATION=python
```

Then re-run above online inference command.

11 Disclaimer

The released components of the Linux Reference Stack for Intel TDX: Virtual Firmware (edk2/TDVF), bootloader (grub2), and the Linux kernel, are fully enabled to be run from within the Linux-based Intel TDX Guest VM to take advantage of the Intel TDX security technology for cryptographically isolating Trusted VMs from the rest of the system.

While Intel TDX removes the need for a Guest VM to trust the host and virtual machine manager (VMM), it cannot by itself protect the guest VM from host/VMM attacks that leverage existing paravirt-based communication interfaces between the host/VMM and the guest (such as MMIO, portIO, etc.). To achieve the full protection against such attacks, the Guest VM SW stack needs to be hardened to securely handle a untrusted and potentially malicious input from a host/VMM via the above-mentioned interfaces. This hardening effort is not specific to Intel TDX as a technology, but common for all confidential cloud computing solutions and the components of the VM guest SW stack. It should be an industry-wide effort together with the open-source maintainers to perform the security analysis and hardening of these components for the confidential computing threat model.

The Linux Reference Stack for Intel TDX team has invested a significant effort in hardening the Linux kernel that is released as part of the Linux Reference Stack for Intel TDX, the threat model for the Linux guest kernel, as well as the implemented mitigation mechanisms are explained in the Intel TDE Linux guest kernel security specification. The overall hardening methodology, as well as documentation on the tools that have been used can be found in Intel TDE guest Linux kernel hardening strategy. As a result, the Linux Reference Stack for Intel TDX kernel tree contains numerous patches that either implement these hardening mechanisms or fix the security issues that were discovered during the hardening process. It is strongly recommended that all these patches are manually carried forward to the intended production kernels, until they are merged into the mainline Linux kernel and will become part of the upstream base kernel tree. In particular, the following two patches that are critical for the security of the Intel TDX Linux guest kernel must be included in any production guest kernel:

Commit ID:

- c942fc241d4e6c215731b6f03740b1a8bfc42018 from patches-tdx-kernelMVP-KERNEL-5.19-v2.4.tar.gz

- Commit ID: c289330c56c61508a1008d74fc65b7bc24a4a7d5 from patches-tdx-kernelMVP-KERNEL-5.19-v2.4.tar.gz

It is important to note that the hardening of the Linux guest kernel has not been finalized for this release and other components, such as virtual firmware (edk2/TDVF) and the bootloader (grub2), still need more attention. In particular, the existing interfaces that edk2/TDVF or grub2 expose towards the host/VMM have not yet been analyzed for potential security implications against the confidential cloud computing threat model. It is strongly recommended that this analysis be done, and any issues uncovered are mitigated before these components are used in production.

12 References

[1] Intel, "Intel® TDX White Papers," February 2023. [Online]. Available: https://www.intel.com/content/www/us/en/developer/articles/technical/intel-trust-domain-extensions.html.

[2] Intel, "TDX Guest Hardening," [Online]. Available: https://intel.github.io/ccc-linux-guest-hardening-docs/tdx-guest-hardening.html.

[3] Confidential Computing Consortium, "A Technical Analysis of Confidential Computing," 2022.

[4] Trust Computing Group, TCG Guidance on Integrity Measurements and Event Log, 2021.