



**OpenSSD Tutorial 2022**

[CRZ Technology](#)





# OpenSSD Introduction

# OpenSSD Motivation



## Need a SSD platform

- to develop a new firmware algorithm
- to explore hardware architecture and organization

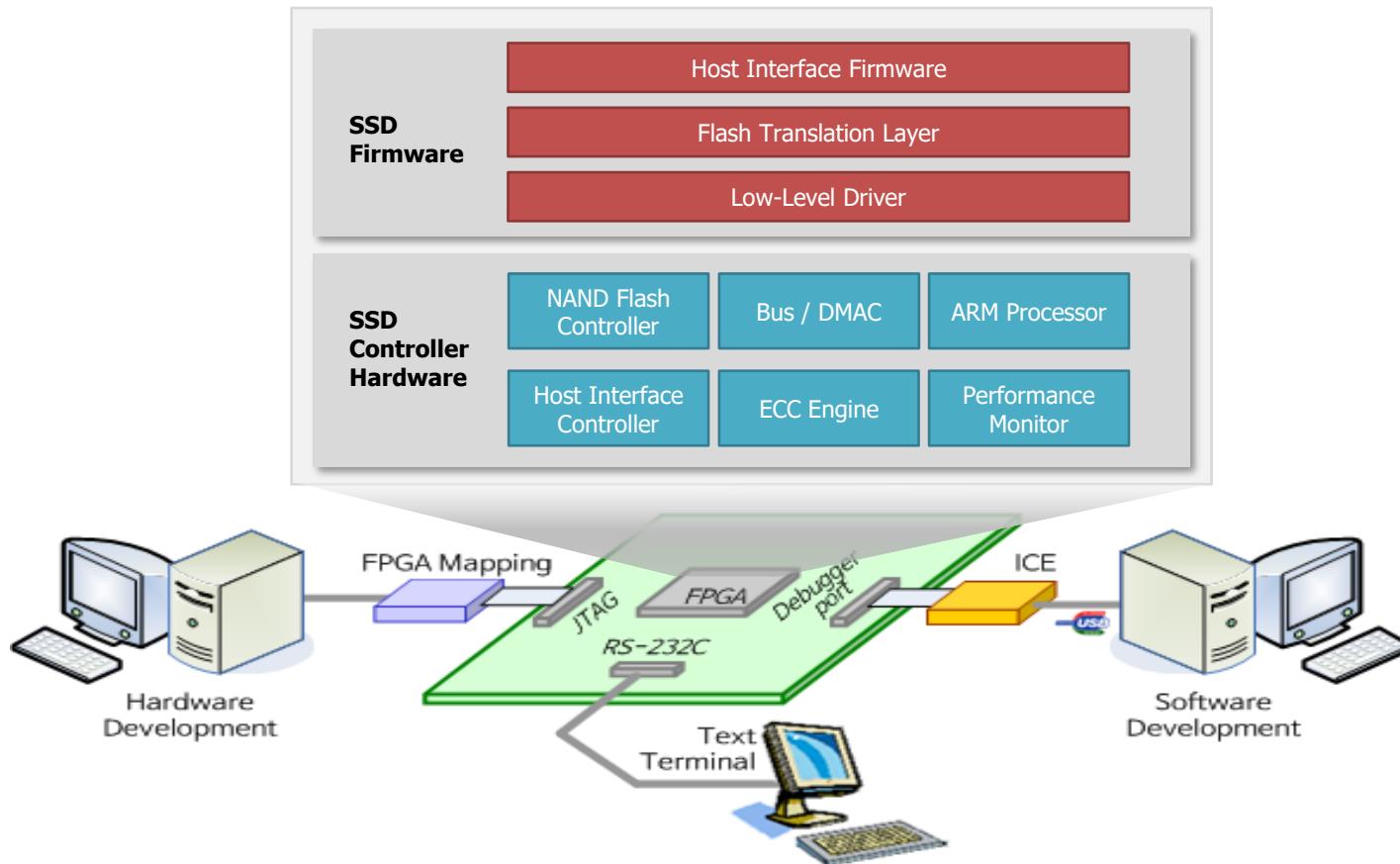


## Use a commercial product as a platform?

- little information on HW/SW
- no way to change controller SoC

# What's the OpenSSD Project?

Open source SSD design used for research and education



# OpenSSD Project History

## ■ Open-source SSD platforms

- Jasmine OpenSSD (2011)
- Cosmos OpenSSD (2014)
- Cosmos+ OpenSSD (2016)
- Daisy+ OpenSSD (2022)

## ■ Daisy+ OpenSSD: FPGA-based platform

- Could modify SSD controller and firmware
- Could add new hardware and software functionality

# Why OpenSSD

## ■ **Realistic research platform**

- Solve your problem in a real system running host applications
- Design your own SSD controller (hardware and firmware), if possible

## ■ **Information exchange**

- Share your solution with people in society

## ■ **Community contribution**

- Open your own solution to public

## ■ **Expensive custom-made storage system**

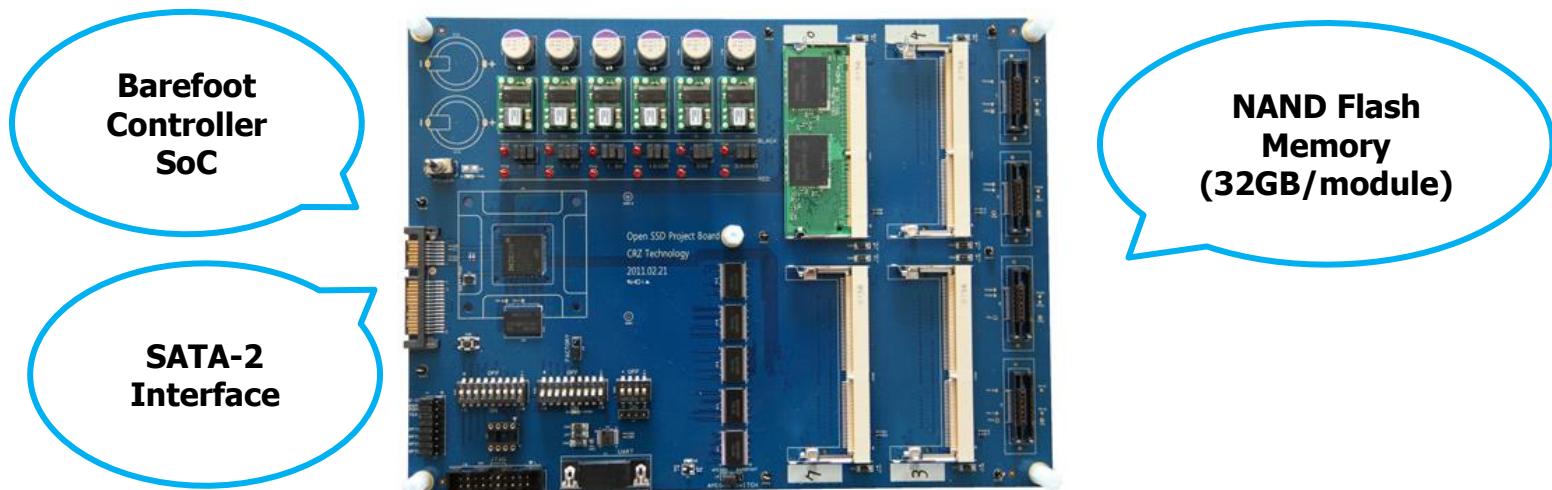
- Unique

## ■ **Play for fun**

# 1<sup>st</sup> OpenSSD (Indilinx)

## ■ Jasmine OpenSSD (2011)

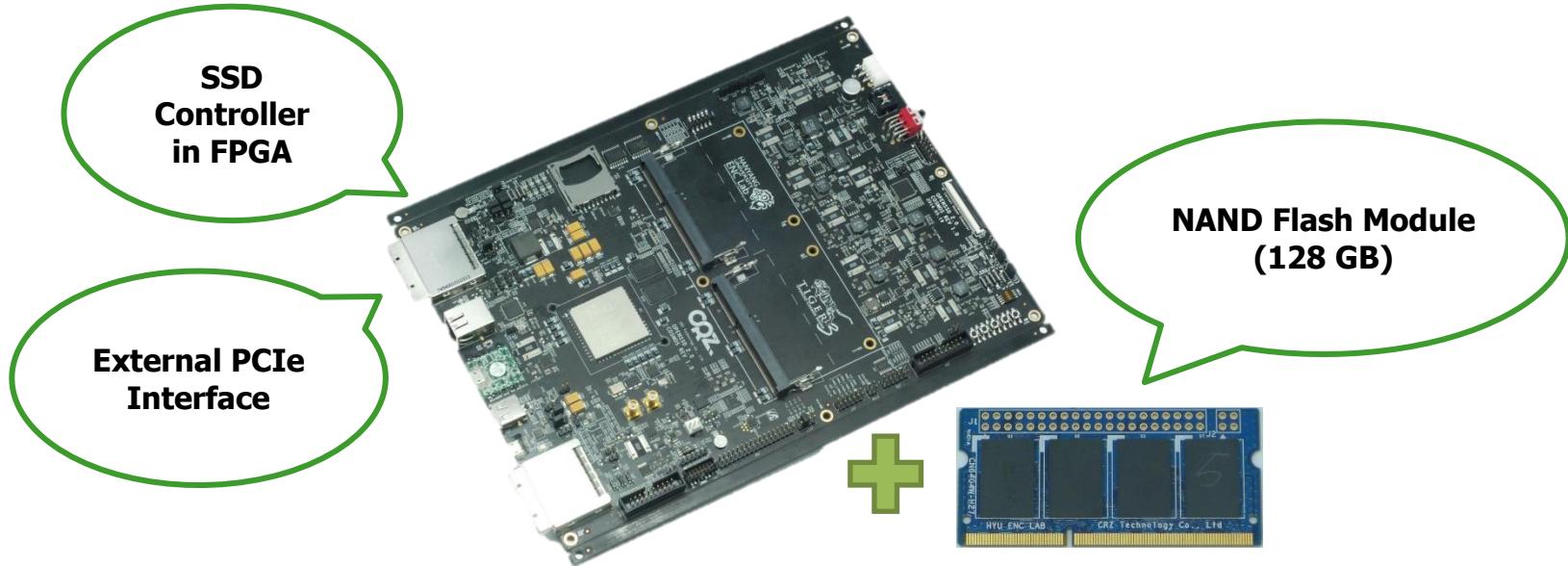
- SSD controller: Indilinx Barefoot (SoC w/SATA2)
- Firmware: SKKU VLDB Lab
- Users from 10+ countries



# 2<sup>nd</sup> OpenSSD (Hanyang University)

## ■ Cosmos OpenSSD (2014)

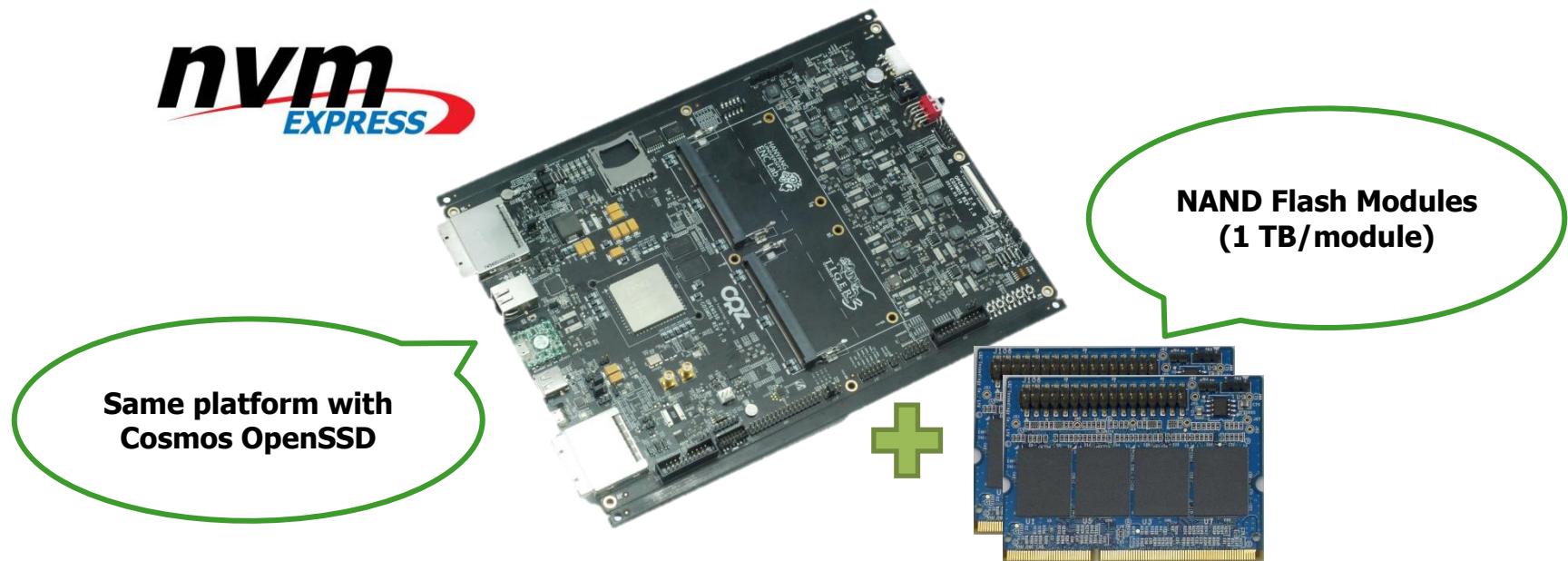
- SSD controller: HYU Tiger 3 (FPGA w/PCIe Gen2)
- Firmware: HYU ENC Lab
- Users from 5 countries (mostly in USA)



# 3<sup>rd</sup> OpenSSD (Hanyang University)

## ■ Cosmos+ OpenSSD (2016)

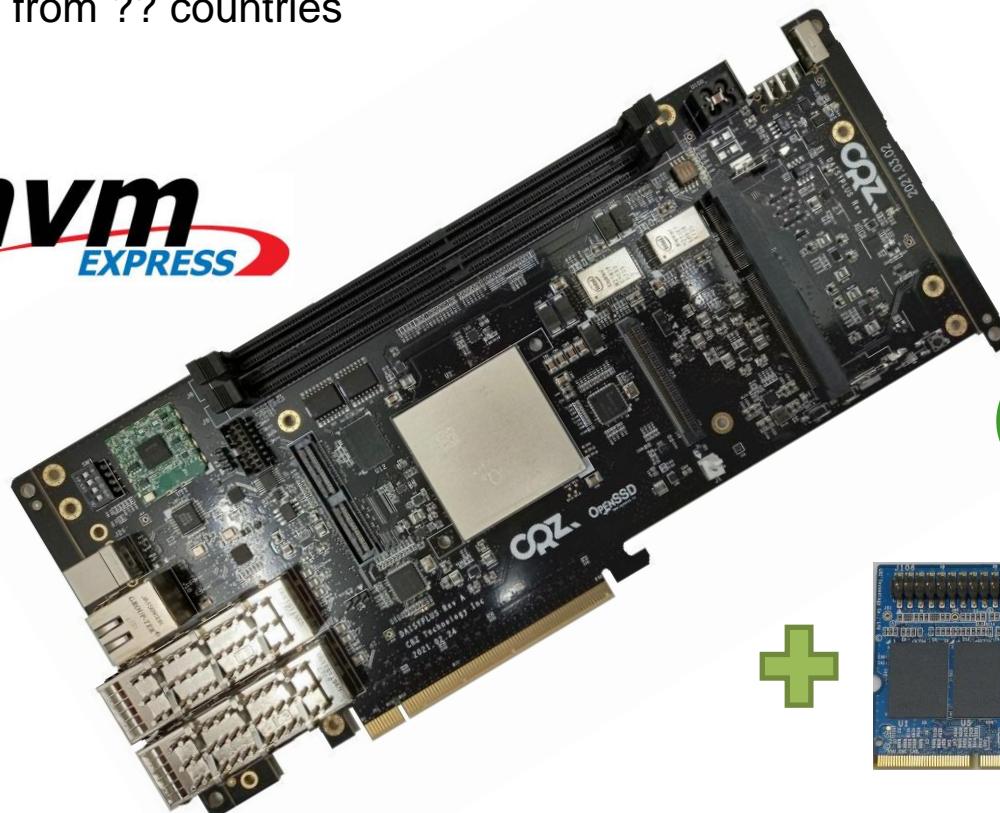
- SSD controller: HYU Tiger 4 (FPGA w/NVMe over PCIe Gen2)
- Same main board with different memory modules
- Firmware: HYU ENC Lab
- Users from ?? countries



# 4<sup>th</sup> OpenSSD (CRZ Technology)

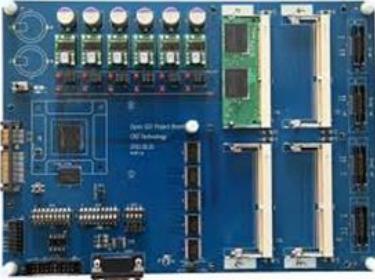
## ■ Daisy+ OpenSSD (2022)

- SSD controller: Daisy+ (FPGA w/NVMe over PCIe Gen3)
- Firmware: CRZ Technology
- Users from ?? countries



**NAND Flash Module  
(256 GB/module)**

# Platform Comparison

	Jasmine OpenSSD	Cosmos OpenSSD	Cosmos+ OpenSSD
Released in	2011	2014	2016
Main Board			
SSD Controller	Indilinx Barefoot (SoC)	HYU Tiger3 (FPGA)	HYU Tiger4 (FPGA)
Host Interface	SATA2	PCIe Gen2 4-lane (AHCI)	PCIe Gen2 8-lane (NVMe)
Maximum Capacity	128 GB (32 GB/module)	256 GB (128 GB/module)	2 TB (1 TB/module)
NAND Data Interface	SDR (Asynchronous)	NVDDR (Synchronous)	NVDDR2 (Toggle)
ECC Type and Strength	BCH, 16 bits/512 B	BCH, 32 bits/2 KB	BCH, 26 bits/512 B

# Platform Comparison

Daisy+ OpenSSD	
Released in	2022
Main Board	
SSD Controller	CRZ(FPGA)
Host Interface	PCIe Gen3 16-lane (NVMe)
Maximum Capacity	256 GB (256 GB/module)
NAND Data Interface	NVDDR2 (Toggle)
ECC Type and Strength	BCH, 26 bits/512 B

# OpenSSD Git Hub

The screenshot shows a GitHub repository page for the project "CRZ-Technology / OpenSSD-OpenChannelSSD". The repository is public and has 36 commits. The main commit message is "CRZ-Technology Added Micron 8C8W designs on CosmosPlus". The repository contains files like .gitattributes, README.md, and subdirectories for CosmosPlus, Daisy, and DaisyPlus. A green callout box highlights the repository URL: <https://github.com/CRZ-Technology/OpenSSD-OpenChannelSSD>. The page also includes sections for Releases, Packages, and Languages.

GitHub - CRZ-Technology/OpenSSD-OpenChannelSSD

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Code Issues Pull requests Actions Projects Security Insights

main 1 branch 0 tags

Go to file Code About

No description, website, or topics provided.

CRZ-Technology Added Micron 8C8W designs on CosmosPlus cd1a47f 6 days ago 36 commits

CosmosPlus Added Micron 8C8W designs on Co 6 days ago

Daisy Added documents 6 days ago

DaisyPlus Added Micron 4C8W designs on DaisyPlus 6 days ago

.gitattributes first commit 11 months ago

README.md Added Micron 8C8W designs on CosmosPlus 6 days ago

README.md

## OpenSSD-OpenChannelSSD

CRZ Technoloy released OpenSSD / OpenChannelSSD sources on CosmosPlus, Daisy, DaisyPlus platforms.

CosmosPlus Directory

- DOC - documents about CosmosPlus
- OpenChannelSSD - Hynix\_NAND - CosmosPlus\_OCSSD\_Hynix\_8C8W\_19.1 - OpenChannelSSD project w/ Hynix
- Toshiba NAND - CosmosPlus OCSSD Toshiba\_RCRW\_19.1 - OpenChannelSSD project w/ Toshi

https://github.com/CRZ-Technology/OpenSSD-OpenChannelSSD

1 fork

Releases

No releases published

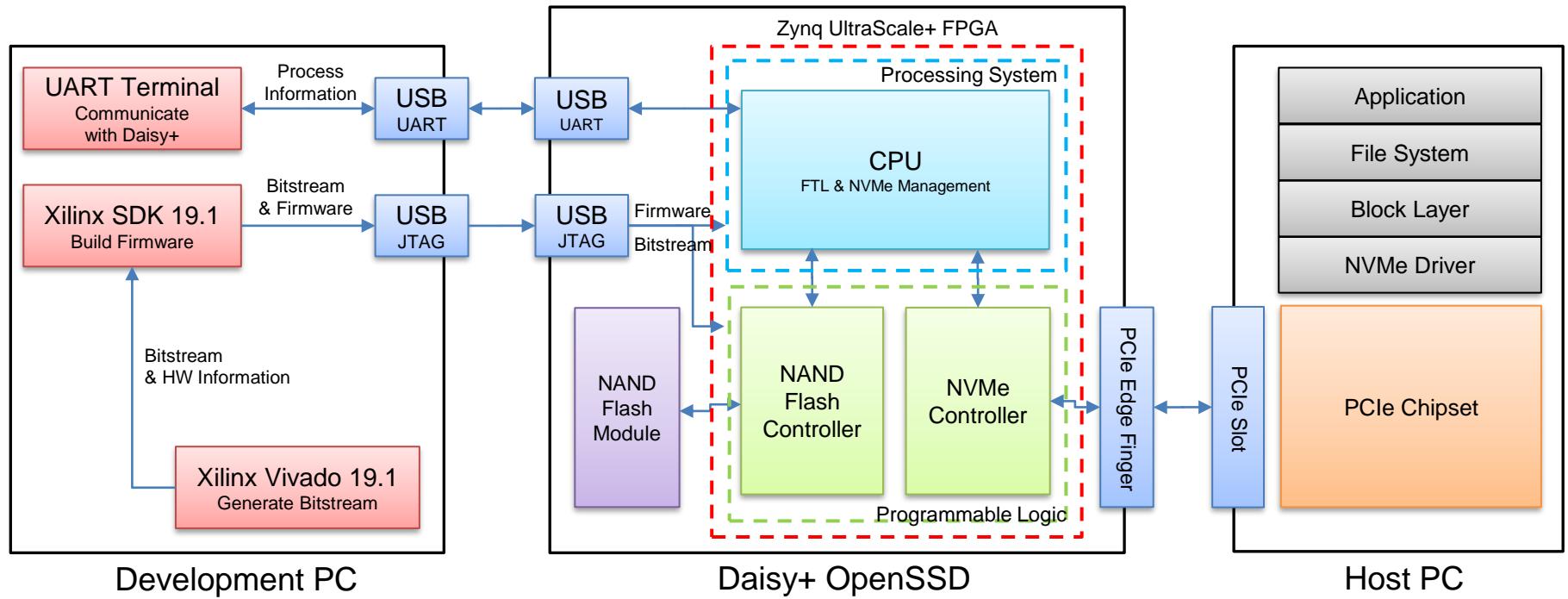
Packages

No packages published

Languages

Language	Percentage
C	26.8%
VHDL	25.9%
Verilog	18.9%
C++	16.5%
HTML	8.1%
Tcl	3.1%
Other	0.7%

# Daisy+ OpenSSD Overview



# Daisy+ OpenSSD Environment

## ■ 1 Development PC

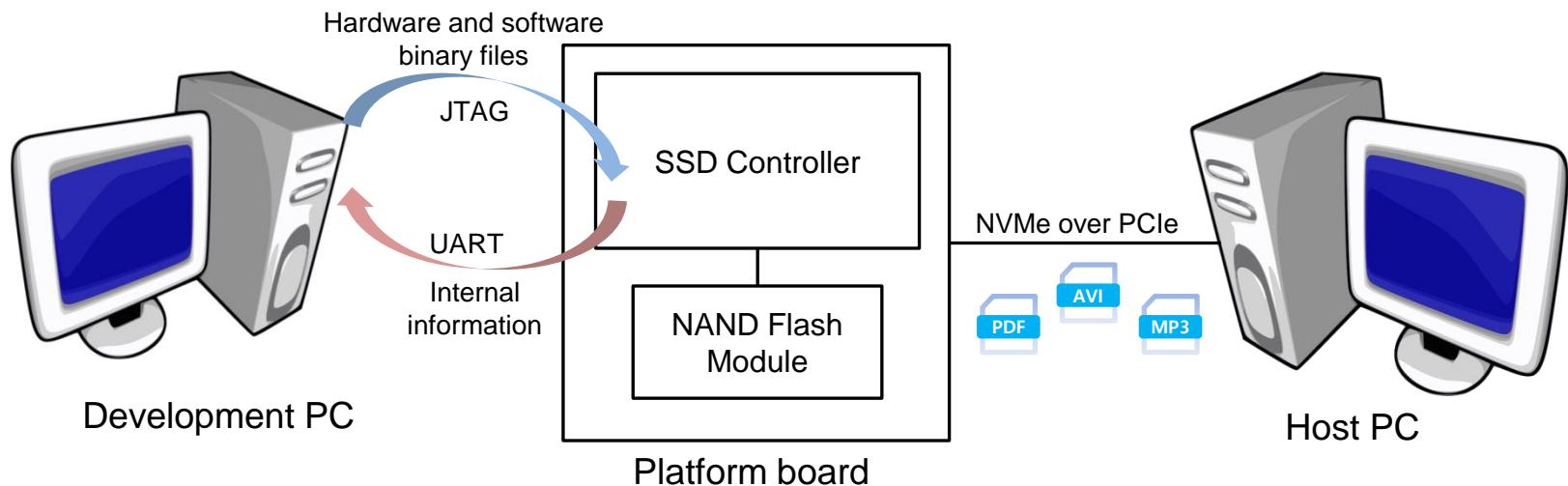
- Downloading hardware/software design (JTAG)
- Monitoring Daisy+ OpenSSD internals (UART)

## ■ 1 Host PC

- Executing applications such as a benchmark (PCIe)

## ■ 1 Platform board with 1 NAND flash module installed

- Working as a storage device to the host PC

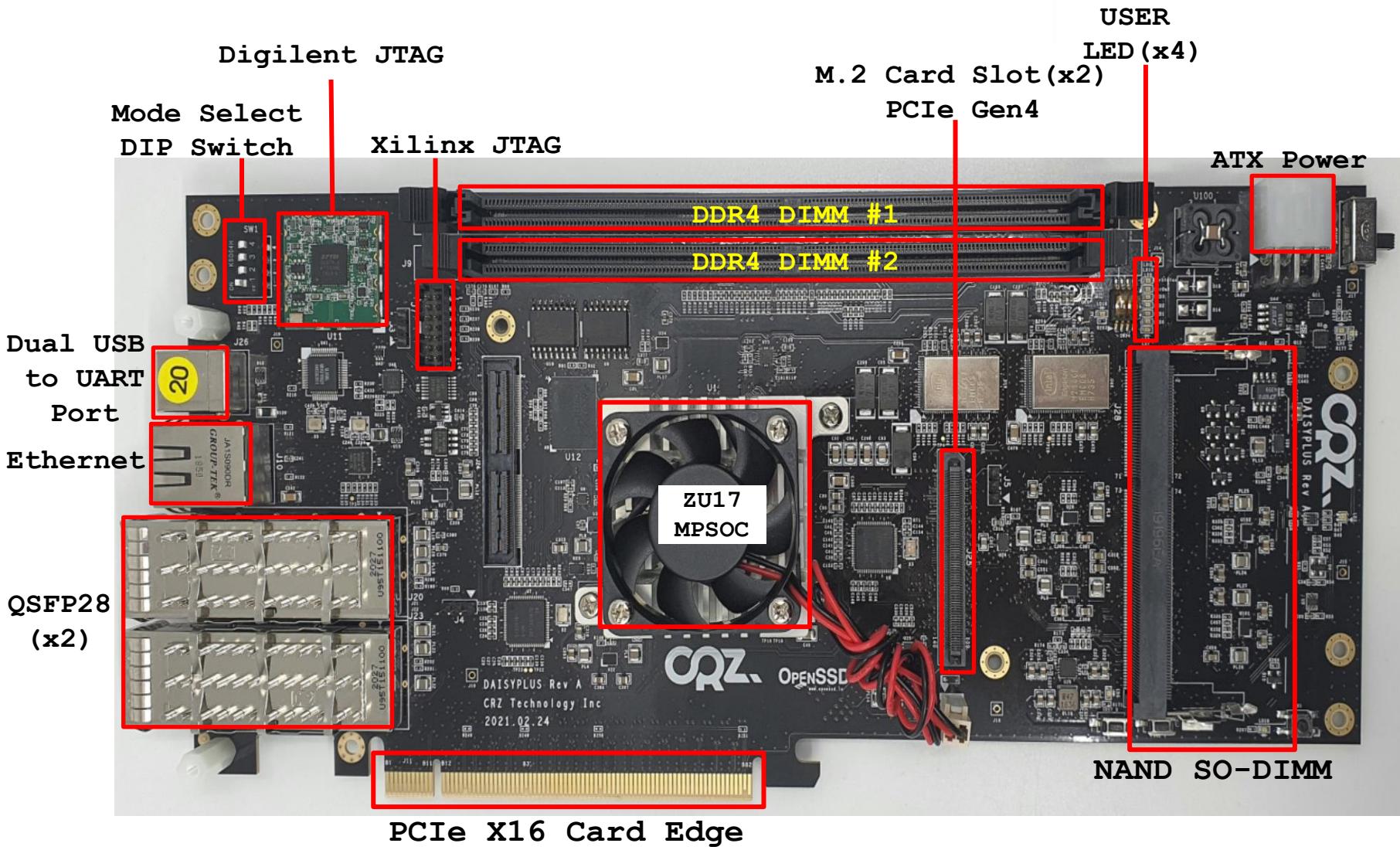


# Hardware Components

- **Daisy+ OpenSSD platform board**
  - Consists of a UltraScale+ FPGA and other peripherals
- **NAND flash module**
  - Configured as multi-channel and multi-way flash array
  - Inserted into Daisy+ OpenSSD platform board
- **PCIe Edge Finger**
  - Connected with host PC through PCIe slot
- **USB cable for JTAG and UART**
  - Connected with development PC
- **Power cable and adapter**
  - 12V supply voltage



# Daisy+ OpenSSD Platform Board



# Primary Details

<b>FPGA</b>		Xilinx Zynq UltraScale+ ZU17EG FPGA (XCZU17EG-2FFVC1760-E)
<b>Logic cells</b>		926K (~ 5.2M ASIC gates)
<b>CPU</b>	<b>Type</b>	Quad-Core ARM Cortex™- A53 / Dual-Core ARM Cortex™- R5
	<b>Clock frequency</b>	Up to 1.5GHz(A53) / Up to 600MHz(R5)
<b>Storage</b>	<b>Total capacity</b>	Up to 256 GB
	<b>Organization</b>	Up to 4-channel 8-way
<b>DRAM</b>	<b>Device interface</b>	LP-DDR4 2400
	<b>Total capacity</b>	2 GB
<b>Bus</b>	<b>System</b>	AXI-Lite (bus width: 32 bits)
	<b>Storage data</b>	AXI (bus width: 64 bits, burst length: 16)
<b>SRAM</b>		256 KB (FPGA internal)

# Zynq-UltraScale+ FPGA Architecture

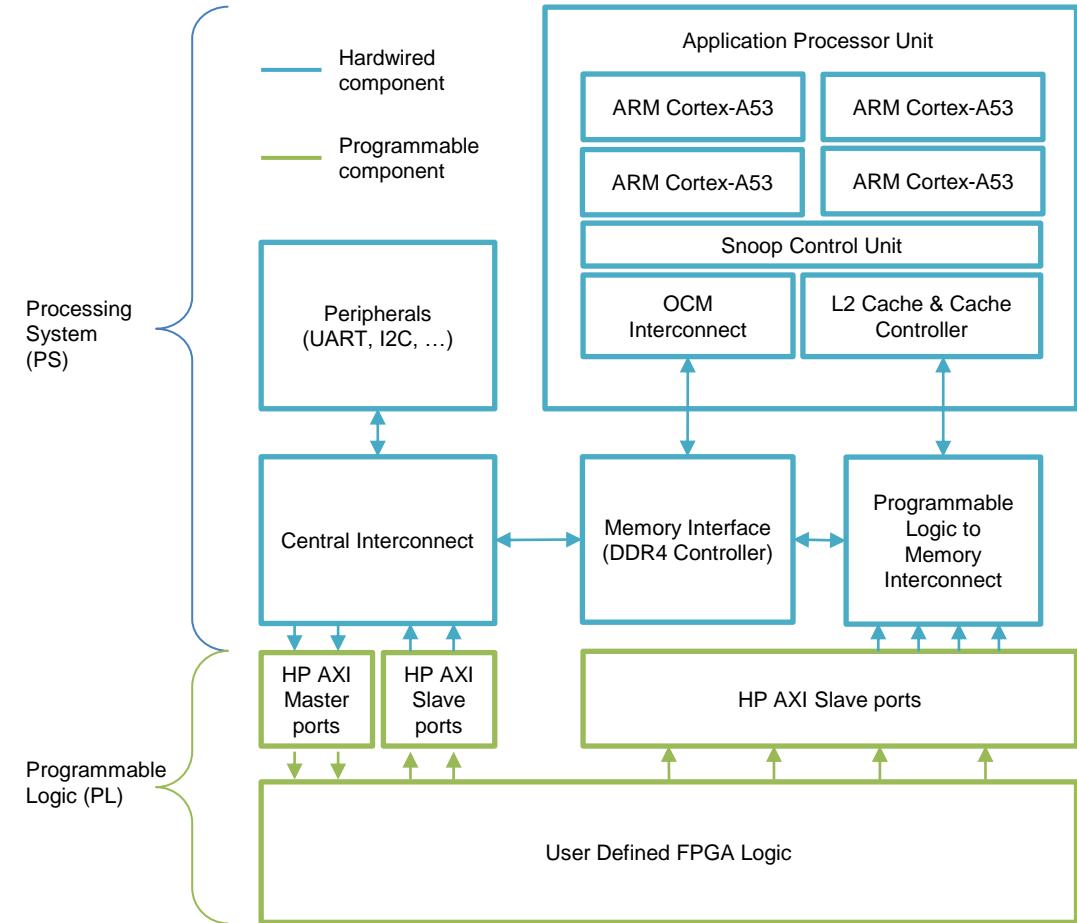
## Xilinx's embedded SoC

### Two regions

- Processing System (PS)
  - Hardwired components
  - Executes the firmware program
- Programmable Logic (PL)
  - Programmable components (FPGA region)
  - NAND flash controller (NFC) and NVMe controller reside in PL

### Benefits of Using Zynq UltraScale+

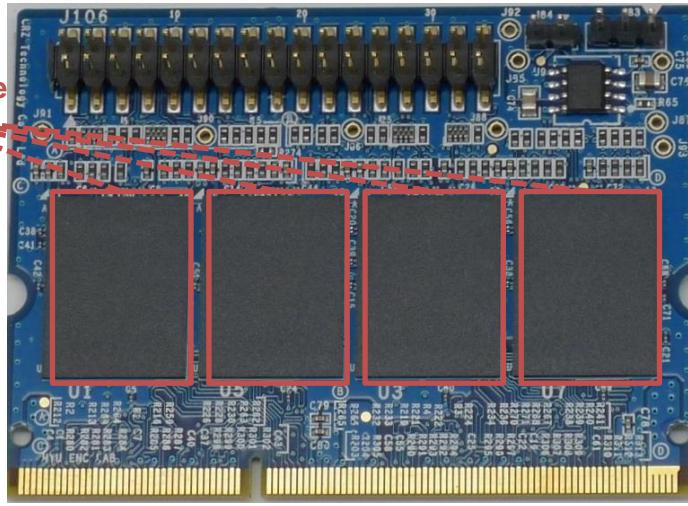
- CPU is more faster than soft core (such as MicroBlaze)
- No need to worry about organizing hardware memory controller, and some other peripherals (such as UART)
- Xilinx supports BSP (Board Support Package)



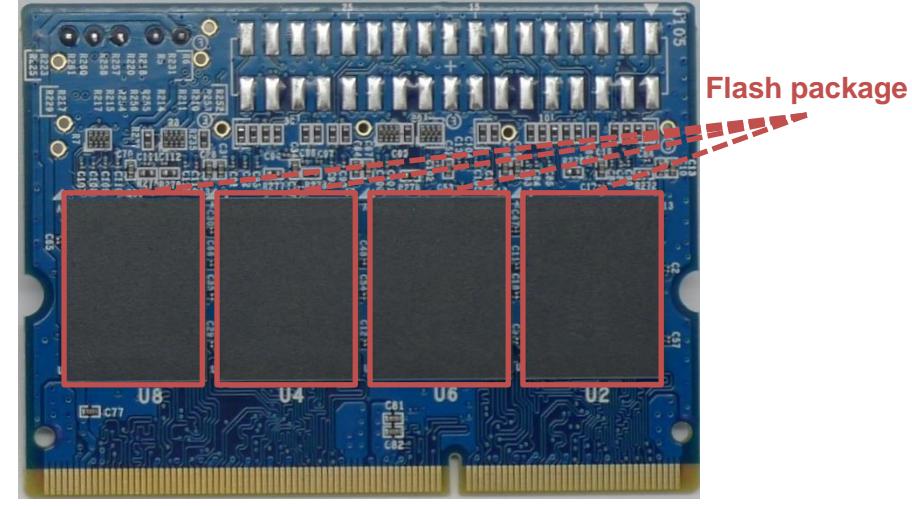
Zynq-UltraScale+ architecture overview

# Daisy+ OpenSSD NAND Module

- Each module has 8 flash packages
  - One flash package
    - Capacity: 32 GB
    - Page size: 18048 Bytes (spare area: 1664 Bytes)
  - Toggle NAND
- Used with CRZ Controller



Front side



Rear side

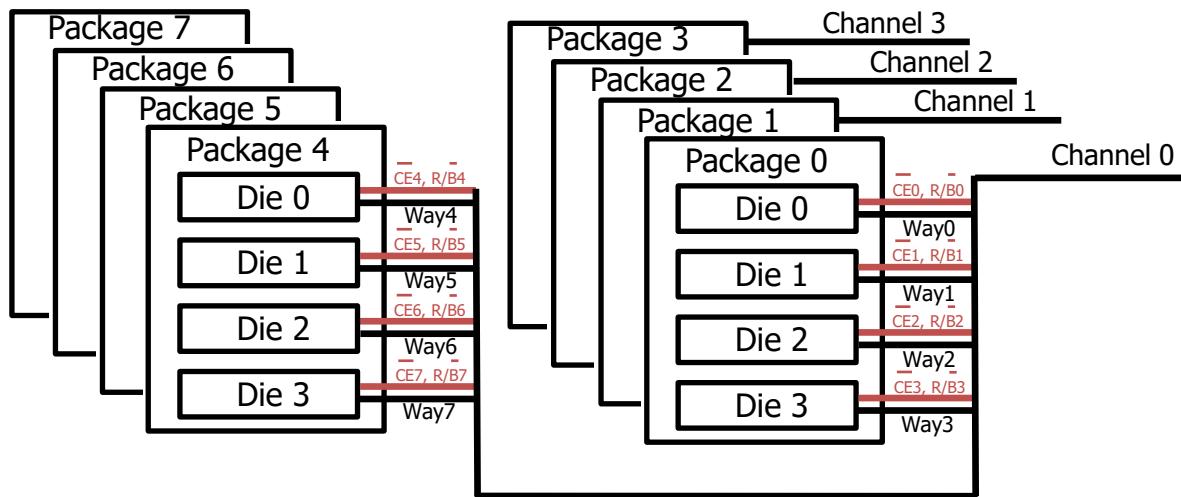
# Logical Organization of NAND Flash Module

## Module configuration

- 4-channels/module and 8-ways/channel

## Shared signals within a channel (a package)

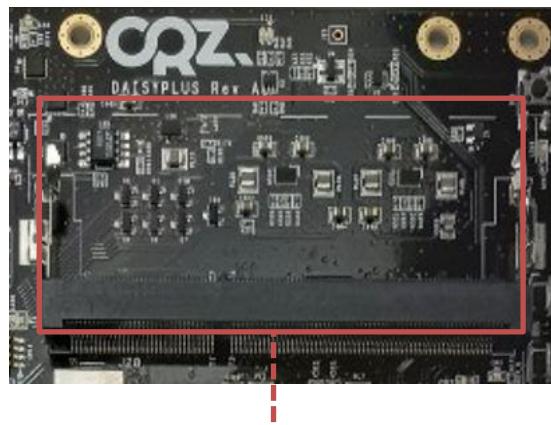
- Dies in the same package share the I/O channel
- Dies in the same package share command signals except Chip Enable (CE)
- Each die has own Ready/Busy (R/B) signal



# NAND Module Setup

## Daisy+ OpenSSD

- Supports one flash module slot (J28)



## Caution

- Daisy+ OpenSSD flash module slots have custom pin maps
- You should not insert any SDRAM module into this slot

# PCIe Extender

- **Expand PCIe Slot of host PC to connect external device**
  - 3M™ Twin Axial PCI Express X16 Extender Assemblies Gen 3.0
  - 8KC3-0726-0250
  
- **External PCIe connector (16-lane) to PCIe Edge Finger**
  - 2.5 GT/s for a Gen1, 5.0 GT/s for a Gen2, 8.0 GT/s for a Gen3
  - Connected with high data rate serial transceiver in FPGA

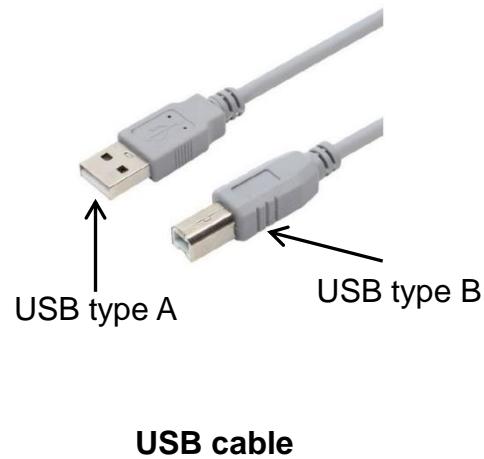


PCIe Extender

# Connection with Development PC

## ■ USB cable

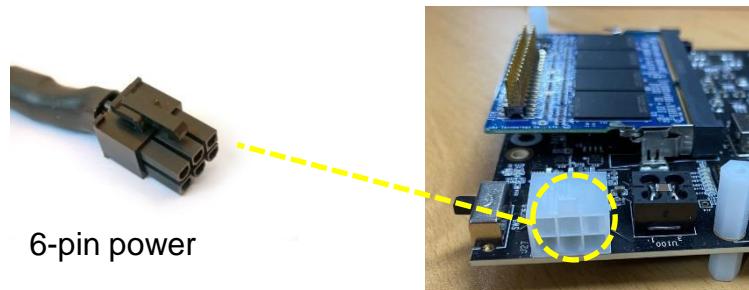
- Used for downloading hardware and software binary files
- Used for monitoring internal processes of Daisy+ OpenSSD
- USB type A to USB type B cable



# Power Connection

## ■ Single-source of power to the platform board

- 6-pin power connector (J27)



## ■ The 6-pin connector looks similar to the regular PC 6-pin PCIe connector

Note: Difference in pin assignment between two connectors

Connector	Pin map					
	1	2	3	4	5	6
Platform board 6-pin power	12V	NC	12V	GND	NC	GND
PC 6-pin PCIe power	GND	GND	GND	12V	12V	12V

## ■ Caution

- Do not plug PC 6-pin PCIe power cable in platform board 6-pin power connector (J27)

# Development Software Components

## ■ Xilinx Vivado

- Generates a FPGA bitstream
- Exports the generated FPGA bitstream to Xilinx SDK

## ■ Xilinx SDK

- Builds a SSD controller firmware
- Downloads a FPGA bitstream and a firmware to the Zynq UltraScale+ FPGA

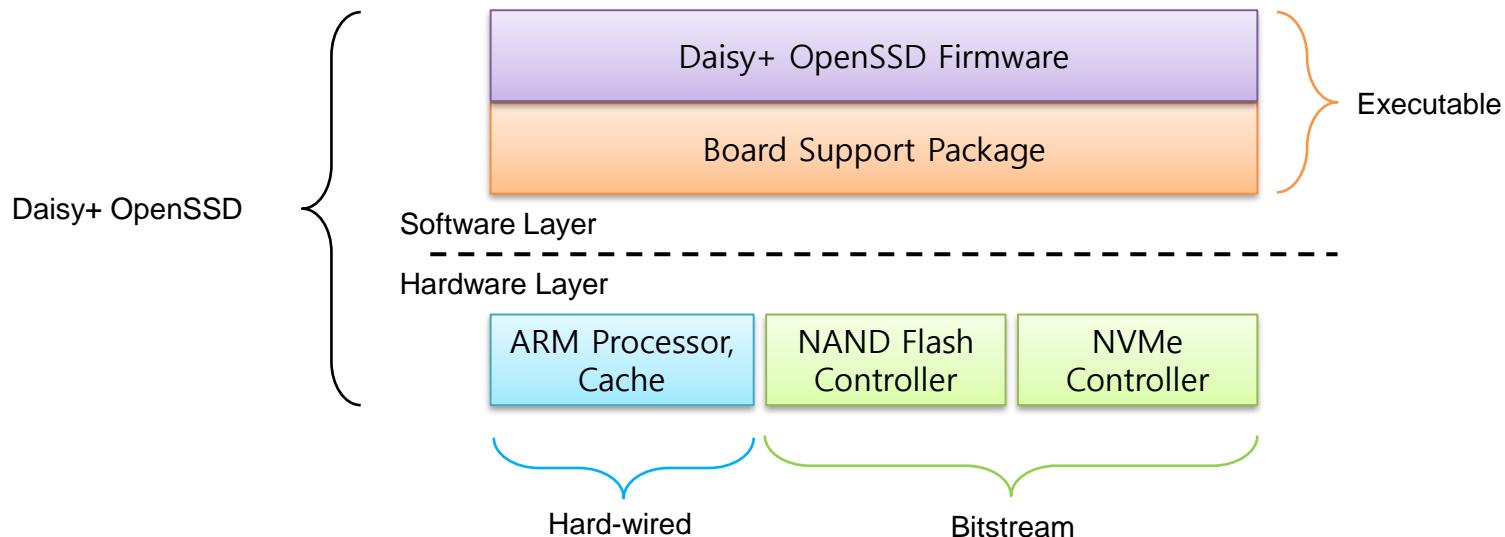
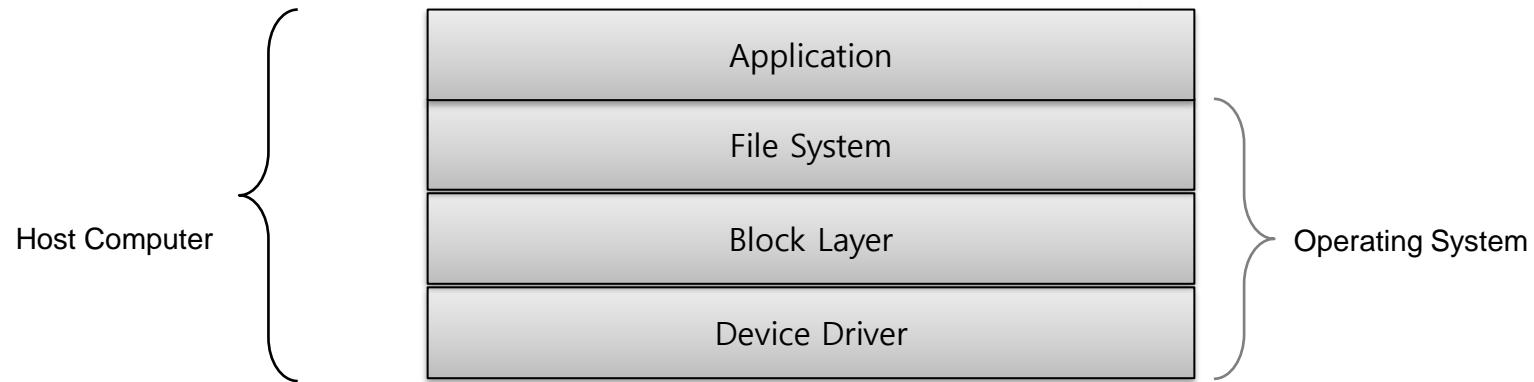
## ■ FPGA bitstream

- Used to configure the programmable logic side of Zynq UltraScale+ FPGA

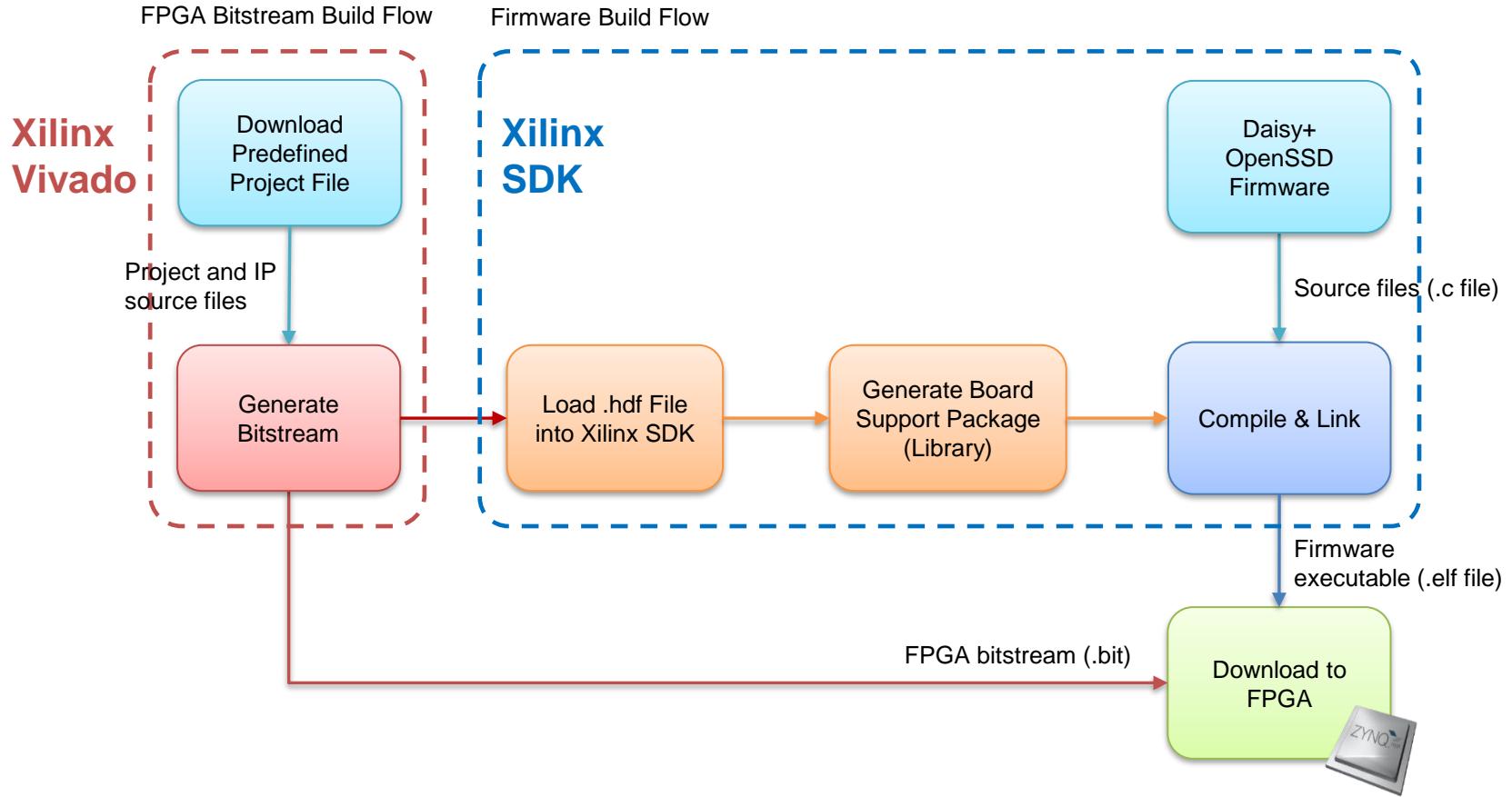
## ■ Firmware

- Manages the NAND flash array
- Handles NVMe commands

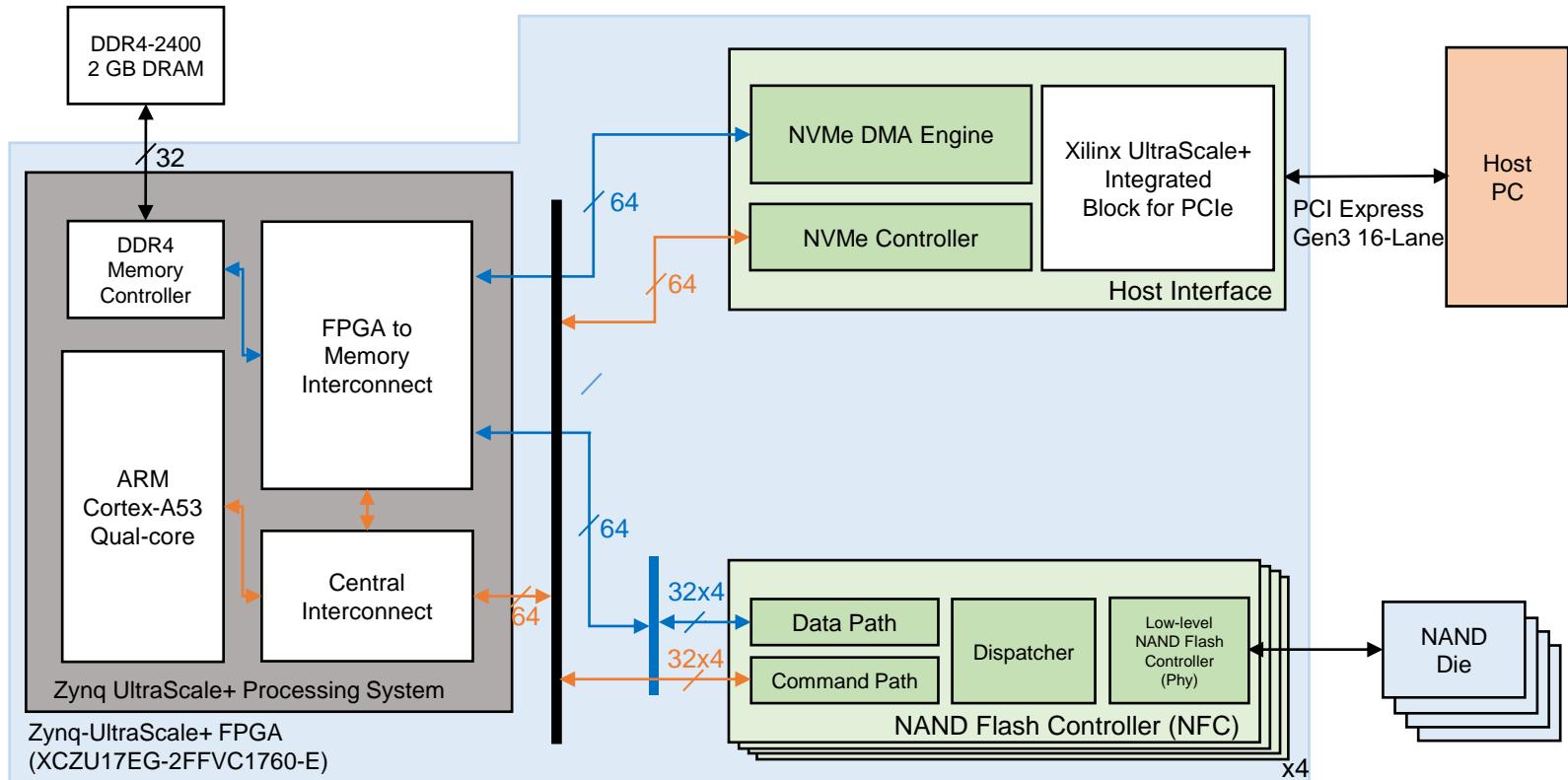
# Host System Software Architecture



# Software Porting Flow



# Daisy+ OpenSSD Internal System Overview



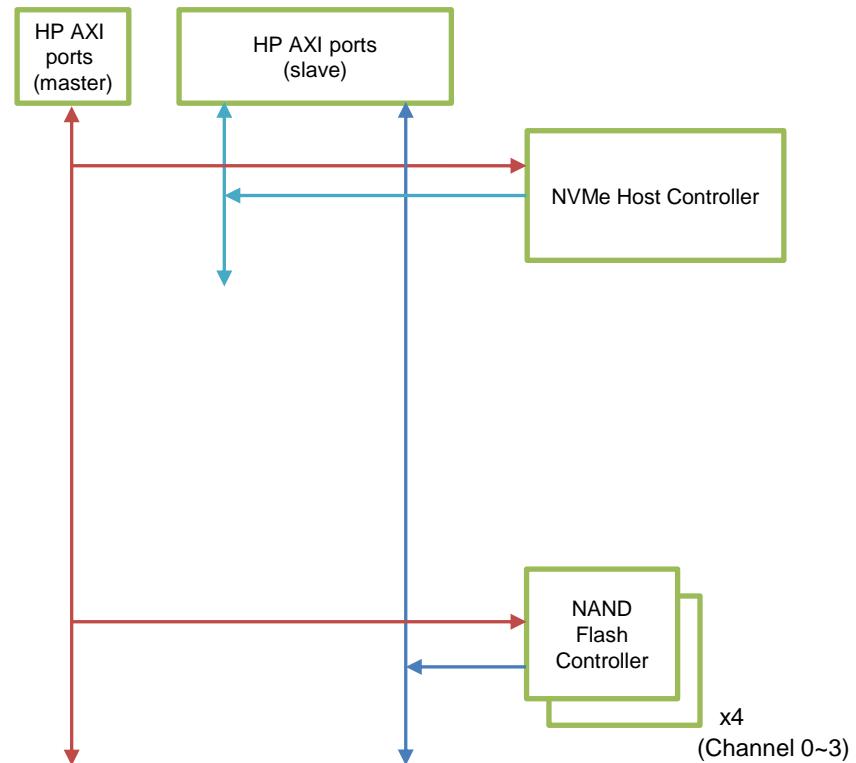
# System Bus Structure

## ■ High Performance (HP) AXI4 bus

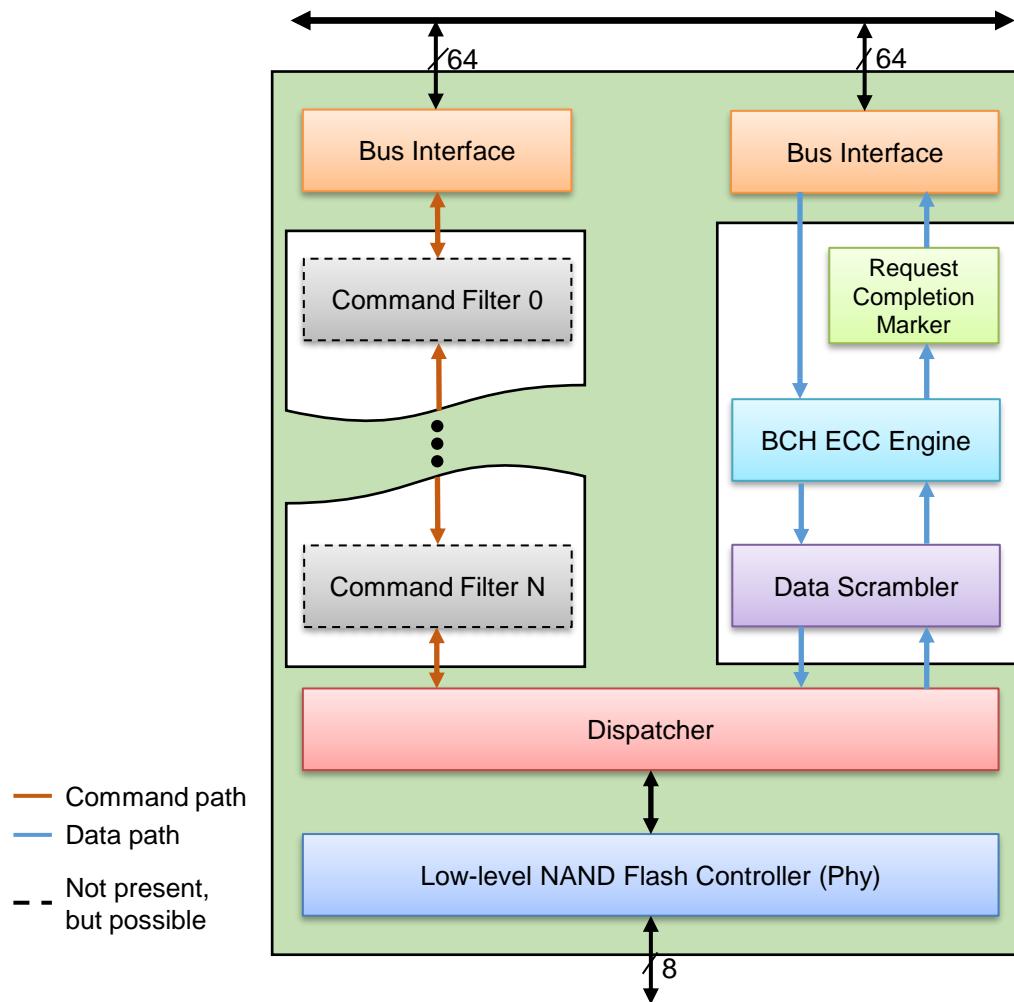
- 64bits interface
- Used for control
- Operates @ 200MHz

## ■ High Performance (HP) AXI4 bus

- 64bits interface
- Used for Direct Memory Access (DMA)
- Operates @ 250 MHz

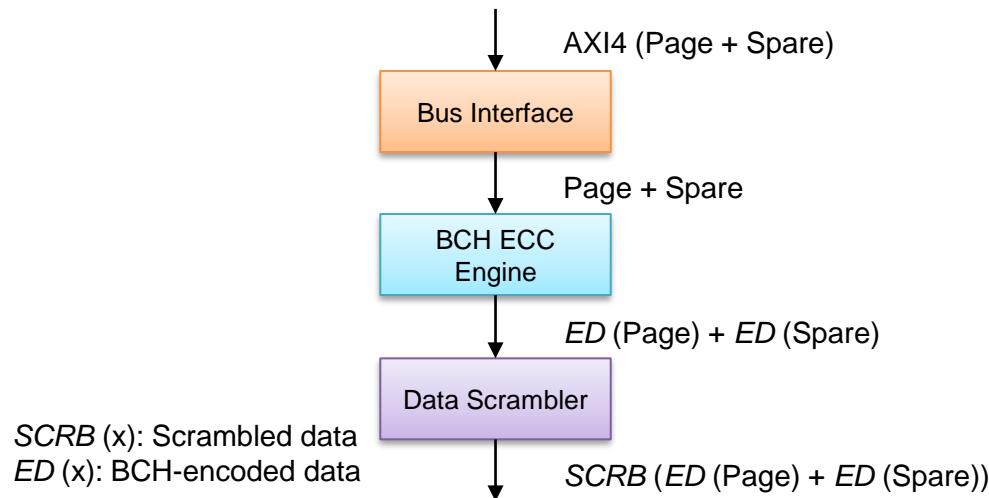


# NAND Flash Controller Overview



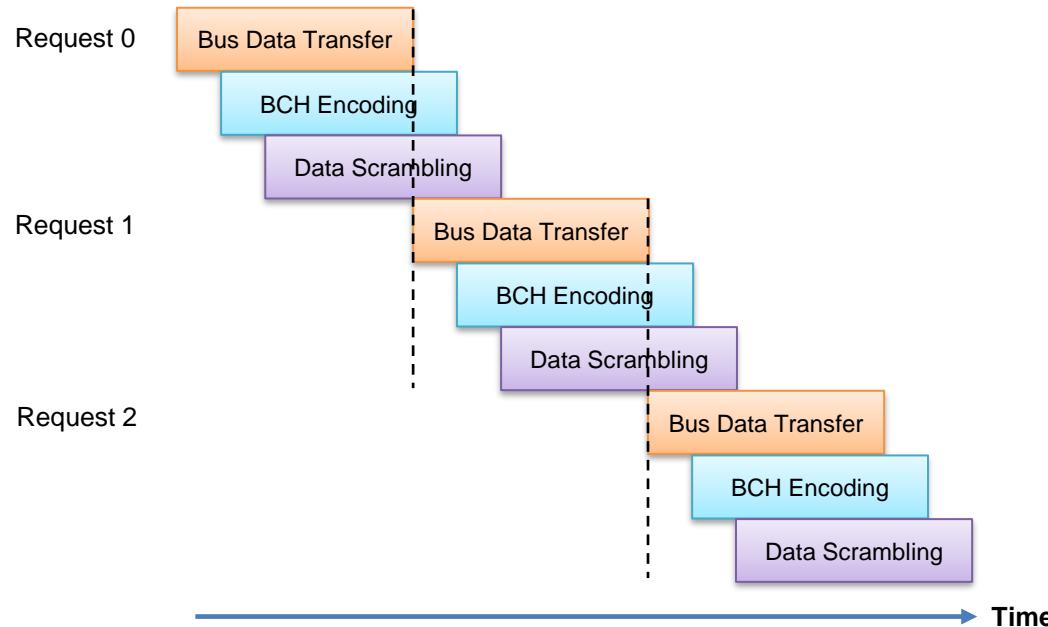
# Layered and Modular NFC Design

- Commands and data streams are encapsulated or decapsulated throughout modules in a layer
- Users can insert or remove modules more easily



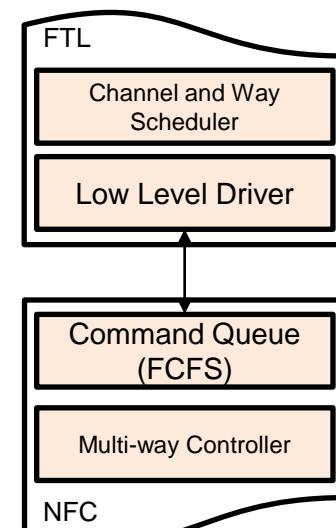
# Pipelined NFC Operation

- Data transfers throughout a layer from DRAM to NAND flash or from NAND flash to DRAM are all pipelined
- Page buffer is not required in channel controller



# Software-controlled NAND Flash Scheduler

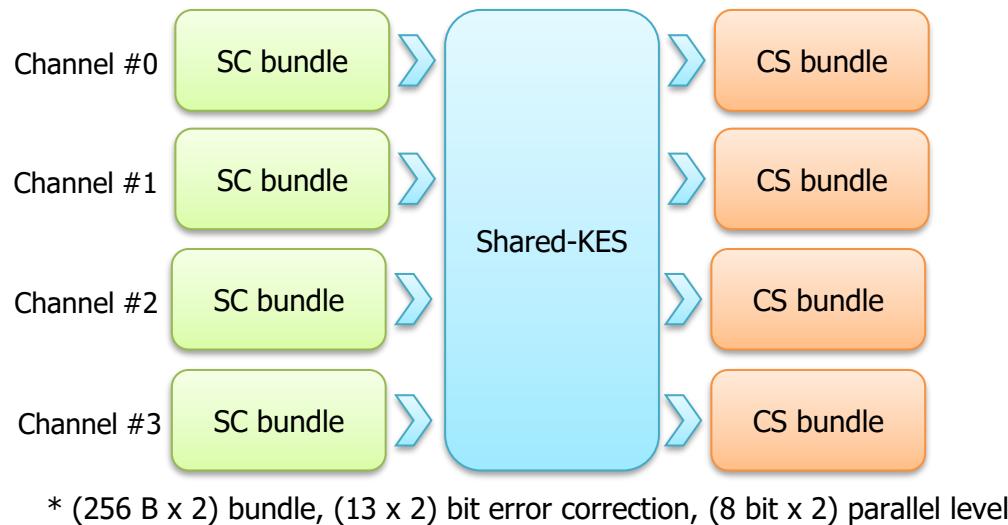
- FTL is responsible for channel and way scheduling
- This enables flexible scheduling policy



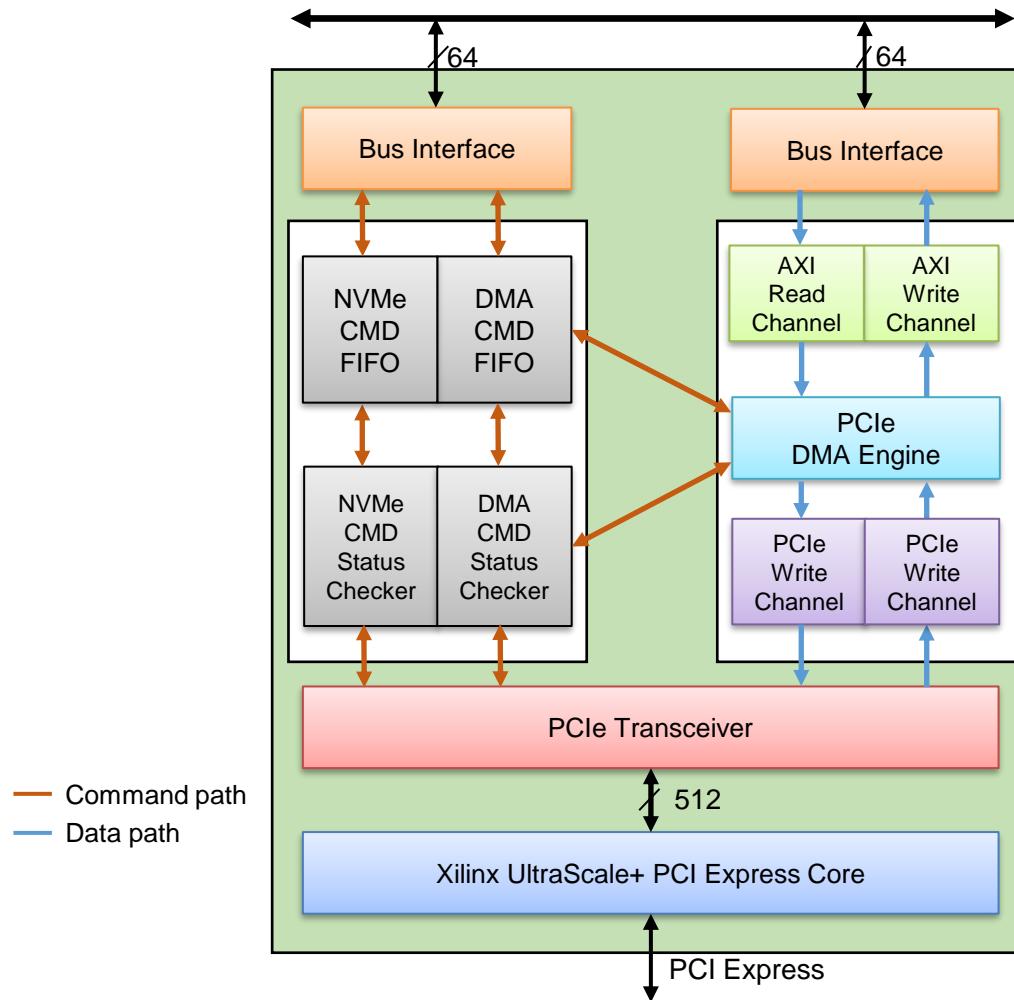
NFC in Daisy+ OpenSSD

# BCH ECC Engine with Shared-KES

- Key equation solver (KES) used more ( $\geq 50\%$ ) of logic cells than syndrome calculator and chien searcher
- Shared-KES saves 40 % of logic cells used in a BCH ECC decoder
- Short BCH code parallelization is applied for high utilization of hardware resources

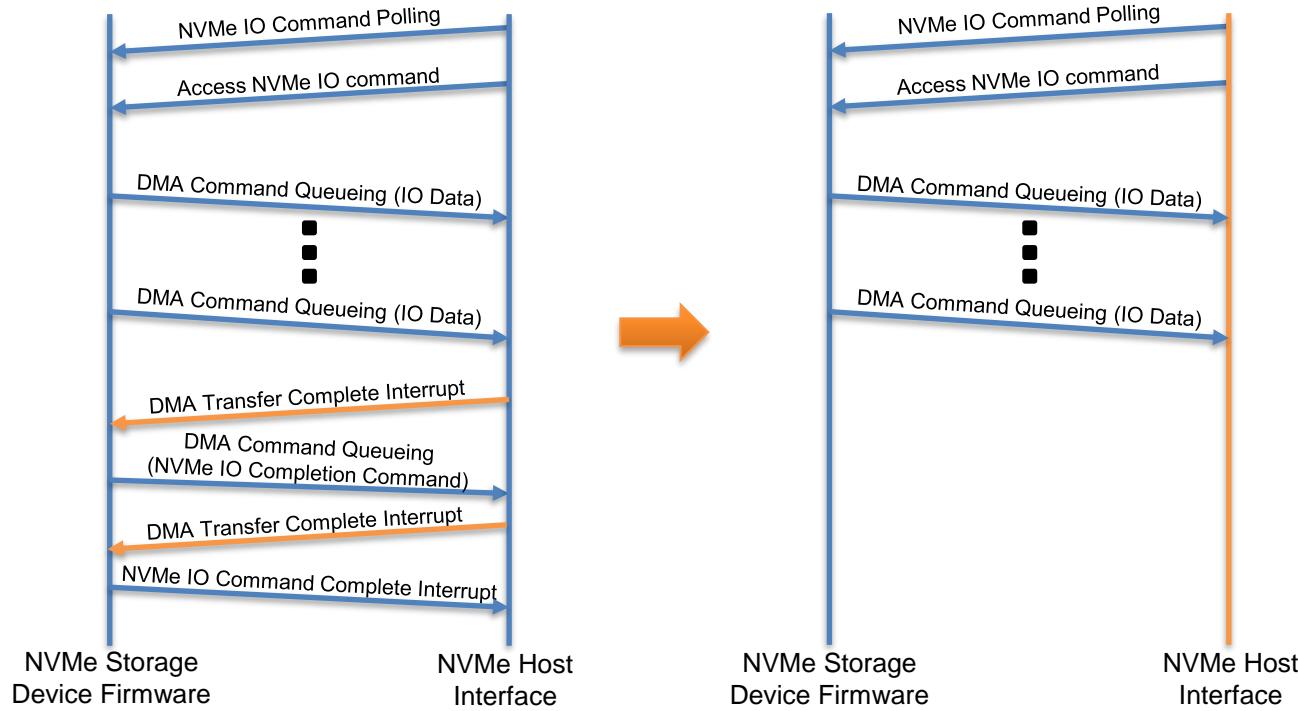


# NVMe Host Interface Overview



# Automated NVMe IO Command Completion

- The NVMe host interface completes NVMe IO commands automatically
- The FTL does not need to be involved in the completion process



# NVMe Host Interface Specification

## ■ NVMe specification 1.1/1.2 compliant

- Up to 8 IO submission/completion queues - 256 entries each
- 512B and 4KB sector size
- Physical region page (PRP) data transfer mechanism
- Native device driver for Windows 8/8.1 and Linux kernel >= 3.3
- OpenFabrics Alliance (OFA) NVMe driver for Windows 7 and later

**NVMe Interface Performance (DRAM Disk)**

Workload	Read	Write
Random 4KB	300K IOPS	300K IOPS
128KB	1.7 GB/s	1.7 GB/s

# Firmware FTL Features

## LRU data buffer management

- Data transfer between host system and NAND flash memory via data buffer
- Eviction of LRU buffer entry

## Pure page-level mapping (16 KB page)

- Static mapping
- Channel/way interleaving

## Greedy garbage collection

- On-demand garbage collection
- Greedy selection of GC victims

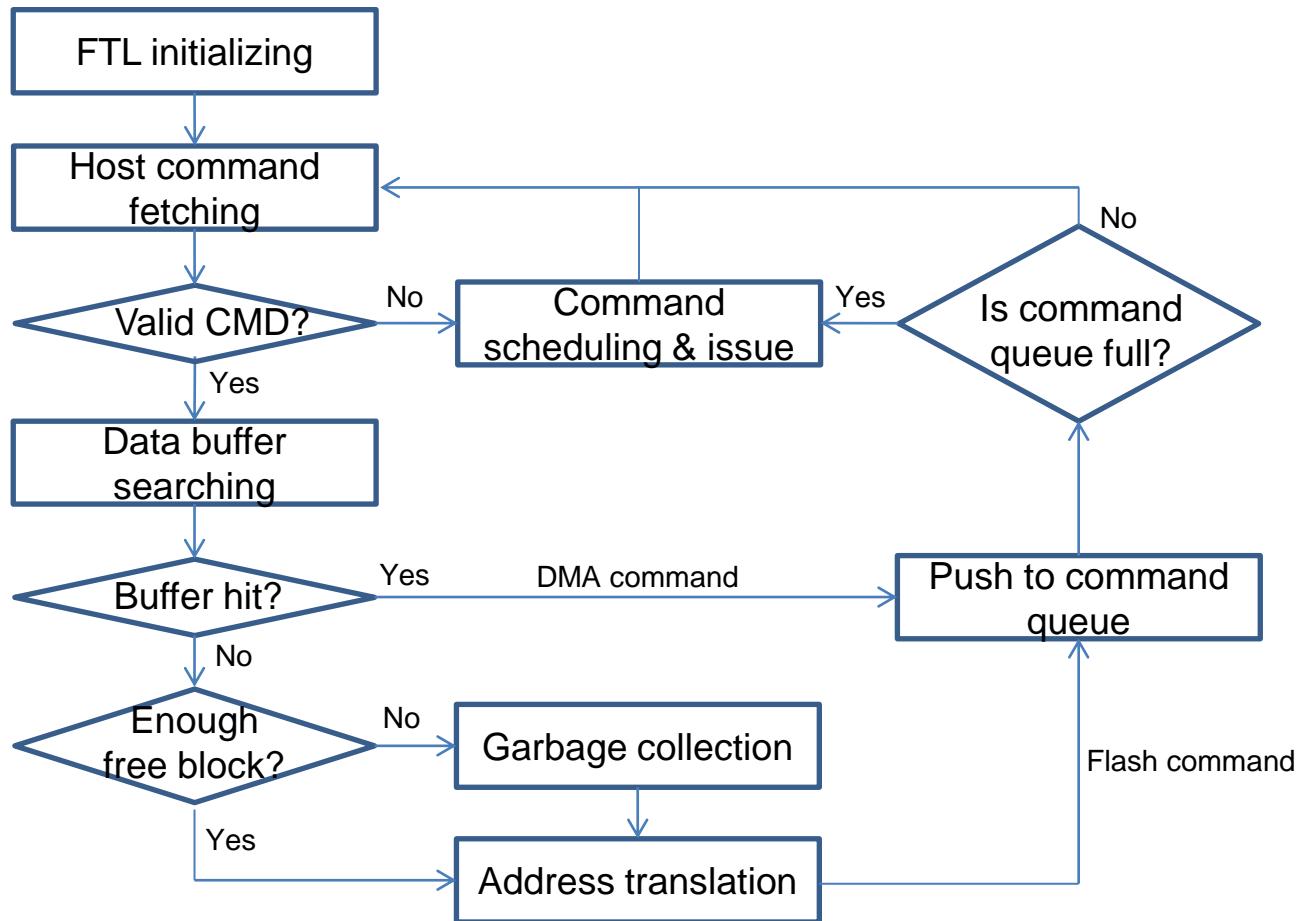
## Command Set

- Single plane flash commands
- DMA commands for data transfer between host system and SSD

## Priority-based scheduling

- Predetermined priority between DMA commands and flash commands
- Out of order execution between commands accessing different flash dies

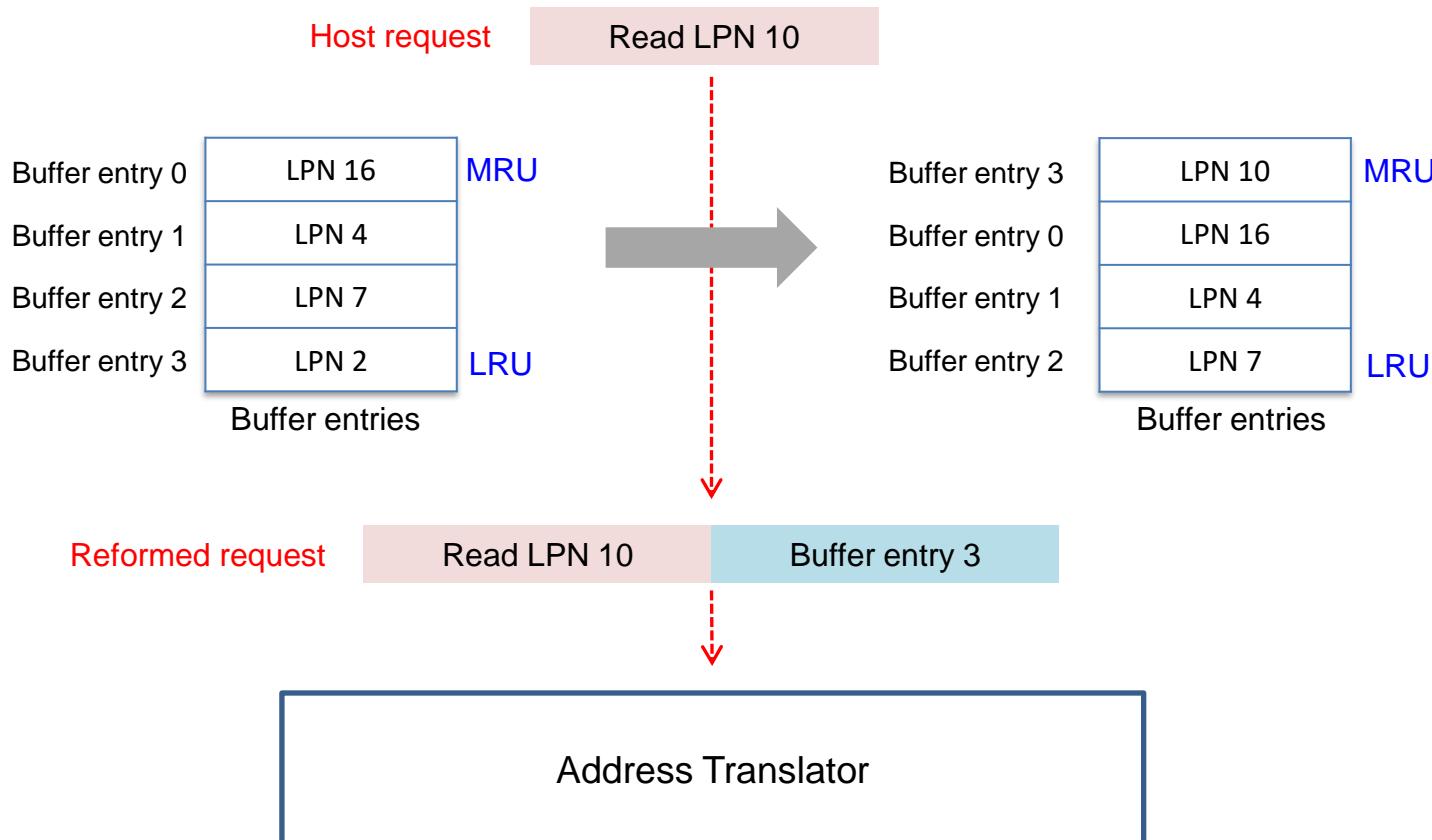
# Firmware Overall Sequence



# LRU Data Buffer Management

## ■ Buffer entry eviction

- LRU buffer entry is evicted to allocate a buffer entry for a new request



# Page-level Mapping

## Main Idea

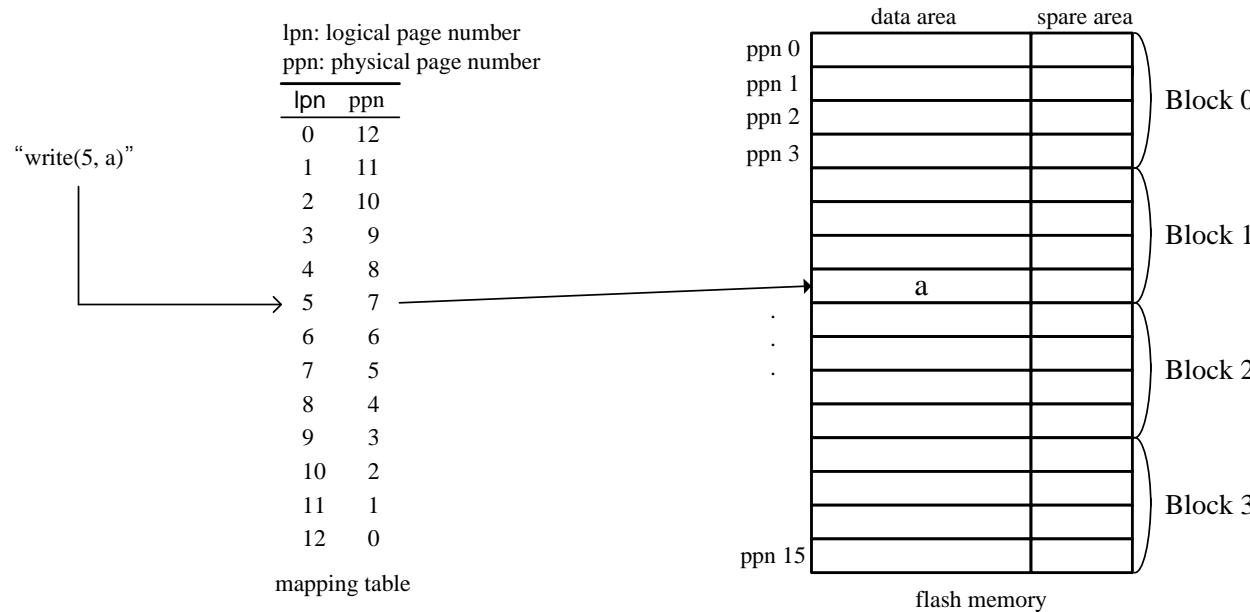
- Every logical page is mapped to a corresponding physical page

## Advantage

- Better performance over random write than block-level mapping

## ■ Disadvantage

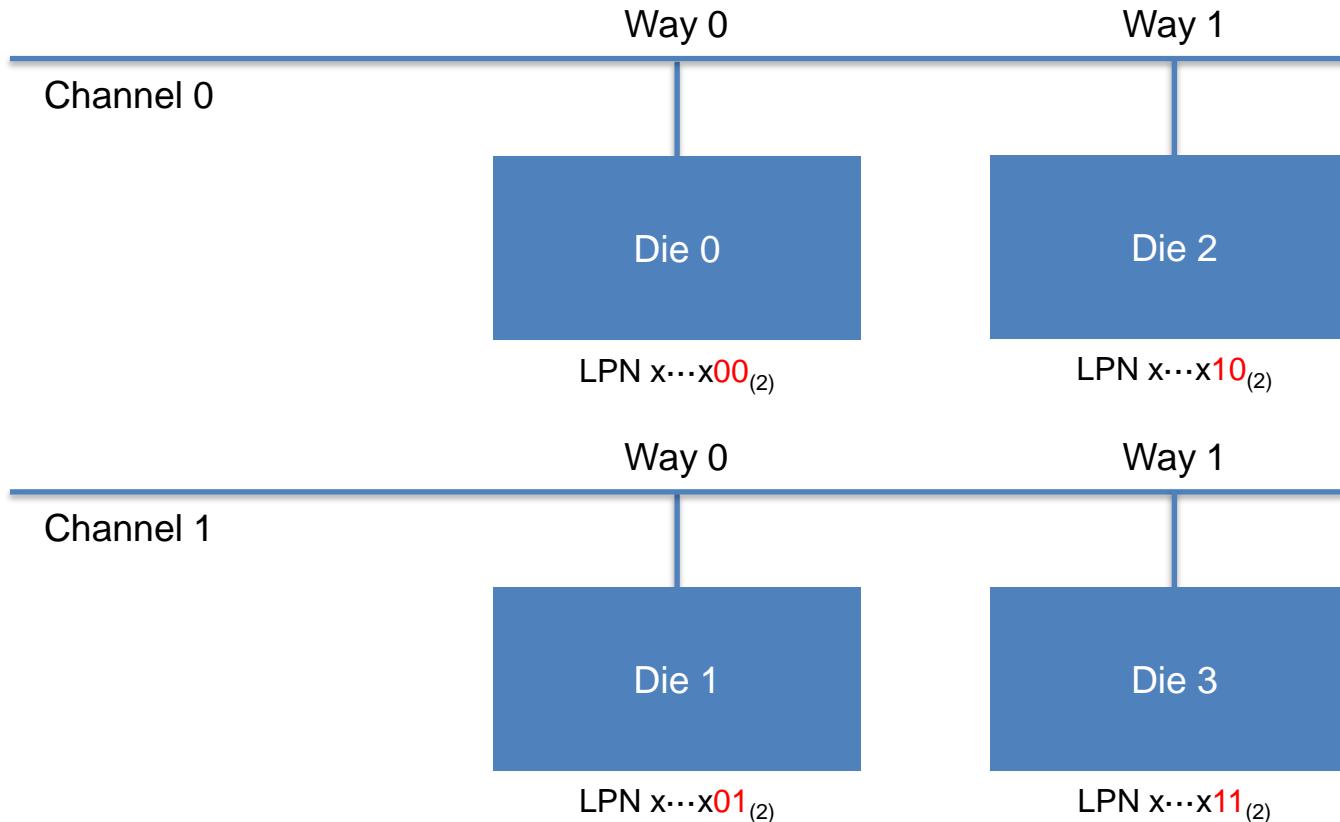
- Huge amount of memory space requirement for the mapping table



# Static Mapping

## ■ Mapping tables are managed within a die

- Simple channel/way interleaving for sequential logical access



Each LPN is deterministically mapped to specific die (ex. 2-channel, 2-way)

# Concept of Garbage Collection

## ■ Why is garbage collection needed

- To reclaim new free blocks for future write requests
  - Invalid data occupy storage space before GC

## ■ What is garbage collection

- Copies the valid data into a new free block and erases the original invalid data
- Basic operations involved in GC are the following
  - 1. The victim blocks meeting the conditions are selected for erasure
  - 2. The valid physical pages are copied into a free block
  - 3. The selected physical blocks are erased

## ■ What is important in GC

- Victim block selection
  - GC time depends on the status of victim block

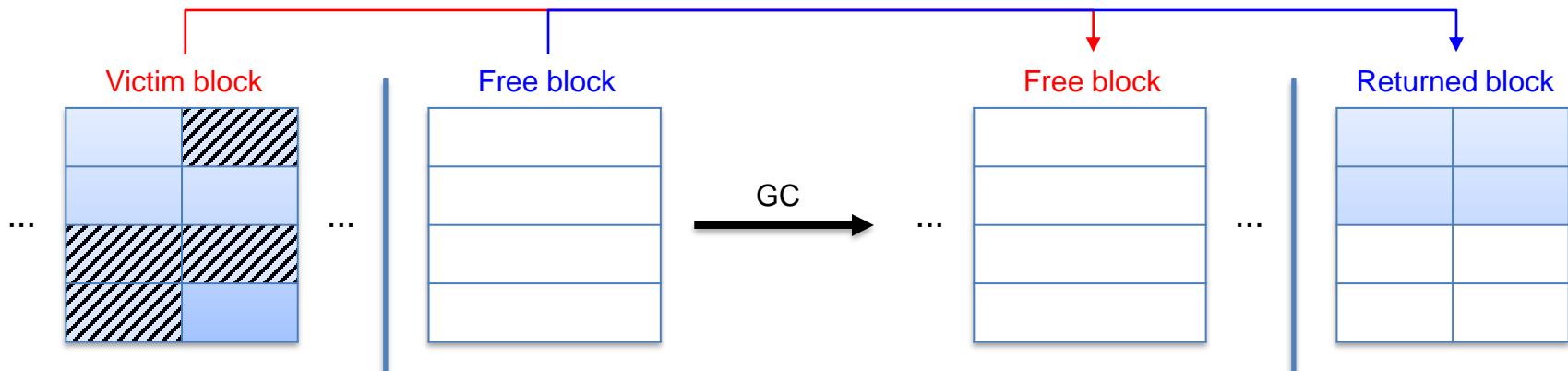
# On-demand GC

## GC Trigger

- Each GC is triggered independently of other dies
- GC is triggered when there is no free user block of each die

## Blocks in GC

- One block per die is overprovisioned
- Single victim block is a target of GC



Valid pages in victim block are copied to free block and the role of two blocks are swapped

# Firmware Command Set

## Commands for NVMe DMA engine

### LLSCommand\_RxDMA

- ▶ Transfer data from host system to data buffer

### LLSCommand\_TxDMA

- ▶ Transfer data from data buffer to host system

## Commands for NAND flash controller

### V2FCommand\_ReadPageTrigger

- ▶ Read data of a flash page
- ▶ Store data to register of the flash die

### V2FCommand\_ReadPageTransfer

- ▶ Transfer data from a flash die to data buffer
- ▶ Inform bit error information to FTL

### V2FCommand\_ProgramPage

- ▶ Transfer data from data buffer to a flash die
- ▶ Program data to a flash page

### V2FCommand\_BlockErase

- ▶ Erase a flash block

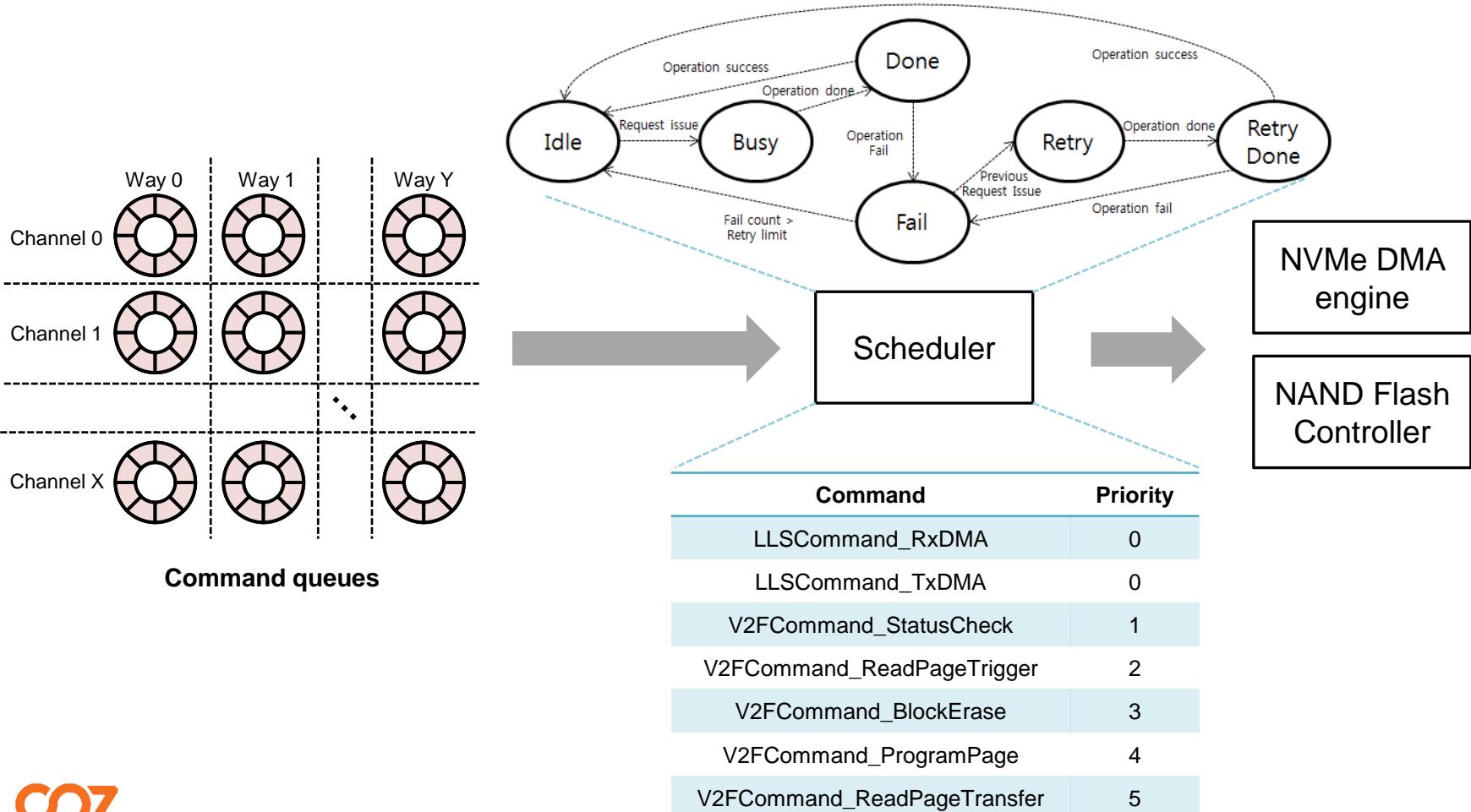
### V2FCommand\_StatusCheck

- ▶ Check a previous command execution result

# Priority-based Scheduling

## Waiting commands are issued by scheduler

- Scheduler checks the state of flash memory controller and host interface controller
- Priority of flash commands enhance multi channel, way parallelism



# Known Restrictions (1/3)

## ■ Firmware

- Supports
  - Buffer management (LRU)
  - Static page mapping
  - Garbage collection (On-demand)
- Not supports
  - Meta flush
  - Wear leveling
- Notice
  - I / O performance can be degraded when performing garbage collection
  - The number of usable blocks is limited when the MLC NAND array is used in the 4-channel 8-way structure
  - The latest firmware in SLC mode accesses only LSB pages of MLC NAND
  - Accessing to MSB pages may cause data errors not able to be corrected by ECC

# MSB Page Data Error Issue

- The bit error rate increases if MSB pages of NAND flash are accessed
- Increased bit errors might not be corrected by BCH error correction engine in the current version of NAND flash controller
- For now, the firmware runs in SLC mode in order to reduce the error rate due to this reason

# Known Restrictions (2/3)

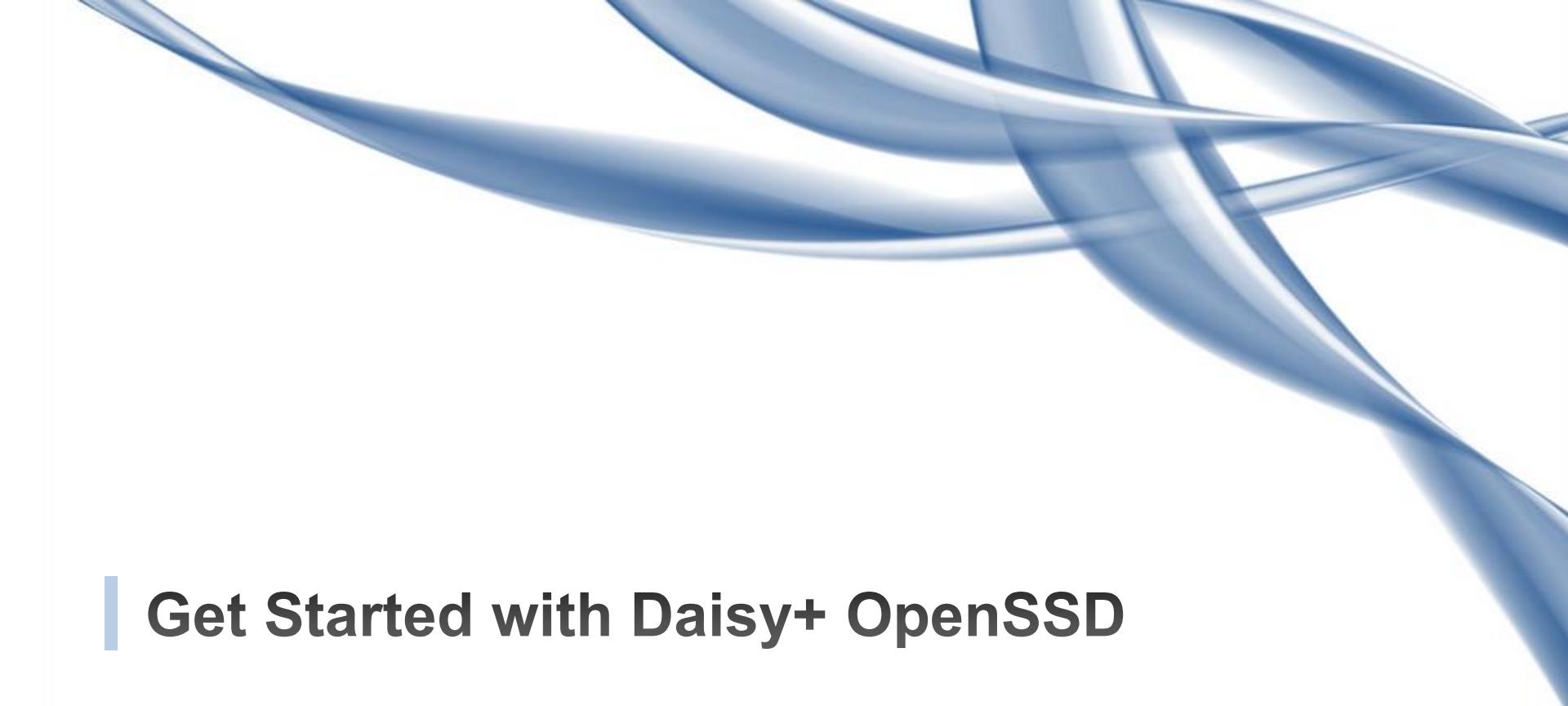
## ■ PCIe-NVMe

- Supports
  - Up to PCIe Gen3.0 x16 lanes
  - Mandatory NVMe commands
  - PRP data transfer mechanism and out-of-order data transfer in PRP list
  - 1 namespace (can be extended by updating firmware)
  - Up to 8 NVMe IO submission queues and 8 NVMe IO completion queues with 256 depths
  - Up to 256 depths internal NVMe command table
  - MSI interrupt with 8 interrupt vectors
  - x86/x64 Ubuntu 14.04 and Windows 8.1
- Not supports
  - 4 byte addressing yet (on debugging)
  - Optional NVMe commands (can be supported by updating firmware)
  - SGL data transfer mechanism
  - Power management (can be supported by updating firmware)
  - MSI-X interrupt
  - Virtualization and sharing features

# Known Restrictions (3/3)

## ■ NAND flash controller

- Supports
  - Channel can be configured up to 4
  - Maximum bandwidth of NAND flash bus 200 MT
- Not supports
  - Additional advanced commands are not supported (e.g. multi-plane operation)



## | Get Started with Daisy+ OpenSSD

# Overall Steps

## ■ Preparing development environment

- Host computer
- Platform board
- Development tools

## ■ Building materials

- FPGA bitstream
- Firmware

## ■ Operating Daisy+ OpenSSD

- Bitstream and firmware download to the FPGA
- Host computer boot and SSD recognition check
- SSD format
- SSD performance evaluation and analysis

# Tested Host PC Mainboard Compositions

Mainboard	BIOS Ver.	Result	Comment
Asrock Z77 Extream 6	P2.40	Working	
ASUS H87-Pro	0806x64	Working	
Gigabyte H97-Gaming 3	F5	Working	
Gigabyte Z97X-UD5H	F8	Working	
	F10c	Not working	4-byte addressing problems in Daisy+ PCIe DMA engine

# Tested Host PC Operating System

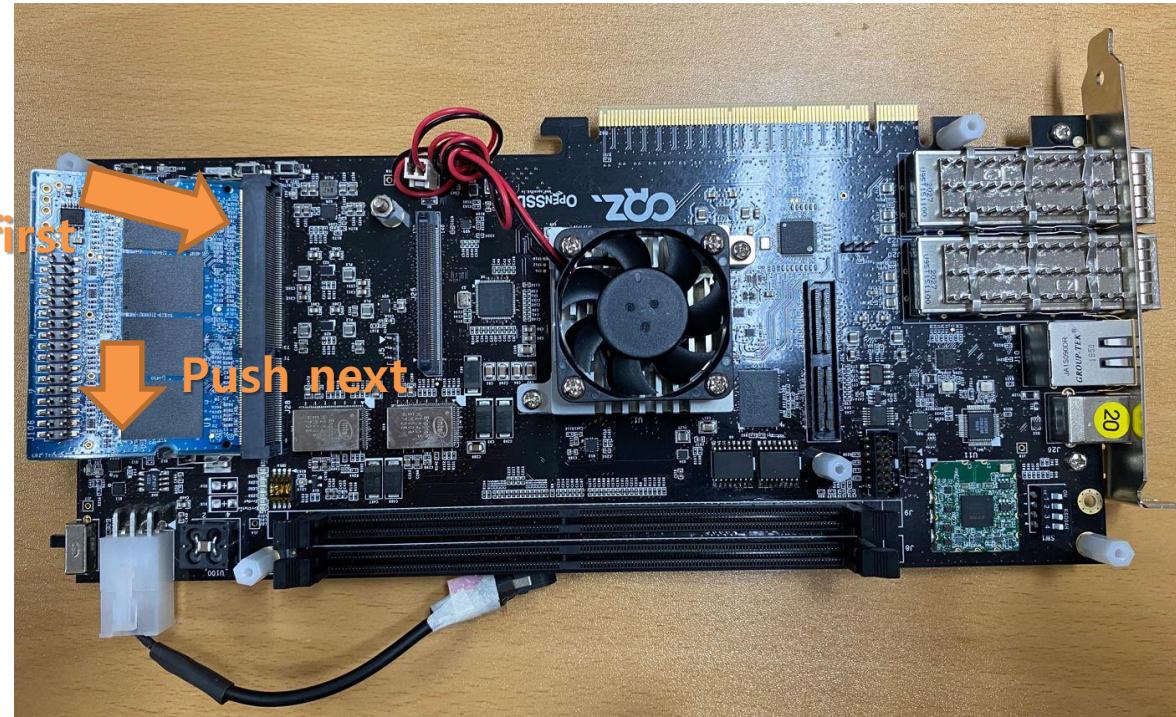
OS	x86/x64	Result	Comment
Windows 7	x64	Working	with OFA driver
Windows 8.1	x64	Working	
Windows 10	x64	Not working	4-byte addressing problems in Daisy+ PCIe DMA engine
Ubuntu 14.04 LTS or above	x64	Working	Kernel version 3.13 or above

# Preparing the Platform Board

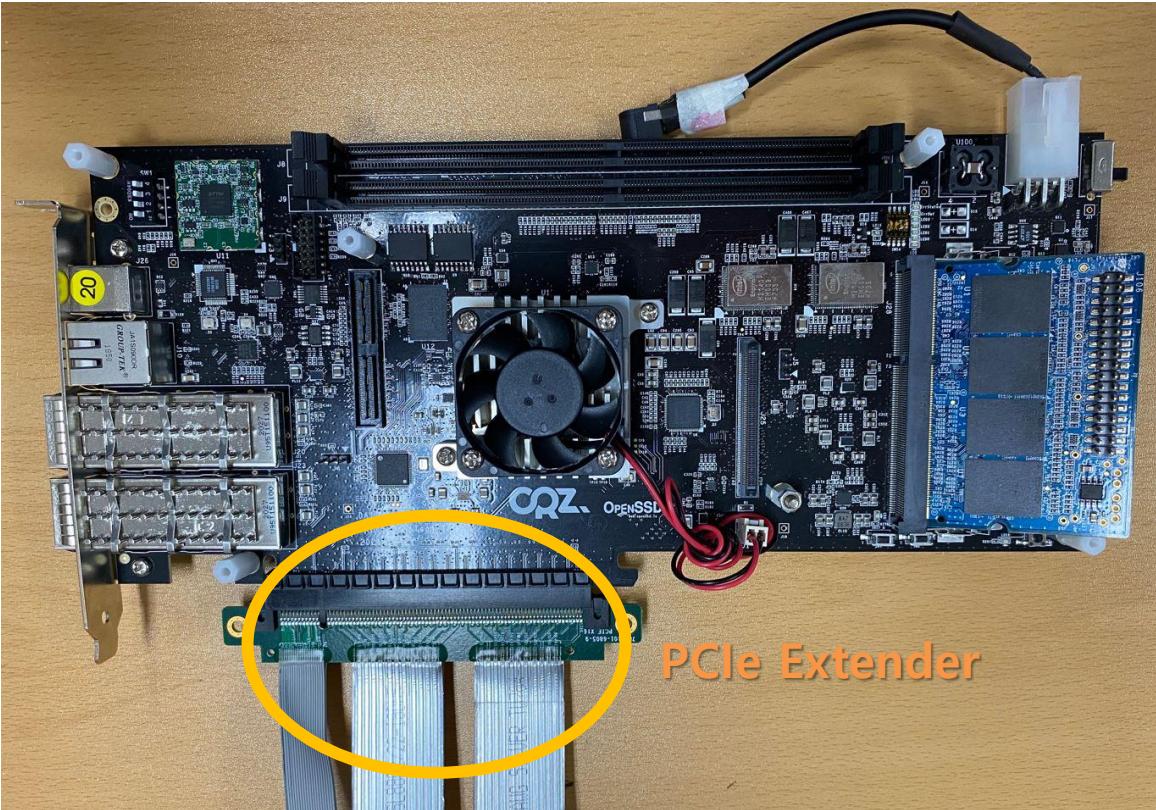
- Insert NAND flash module
- Connect the PCIe extender
- Connect the USB cable for jtag / UART
- Connect the power cable

# Insert NAND Flash Module

- A single NAND flash module can support up to 4-channel configuration

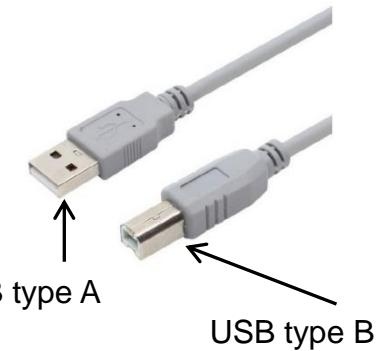
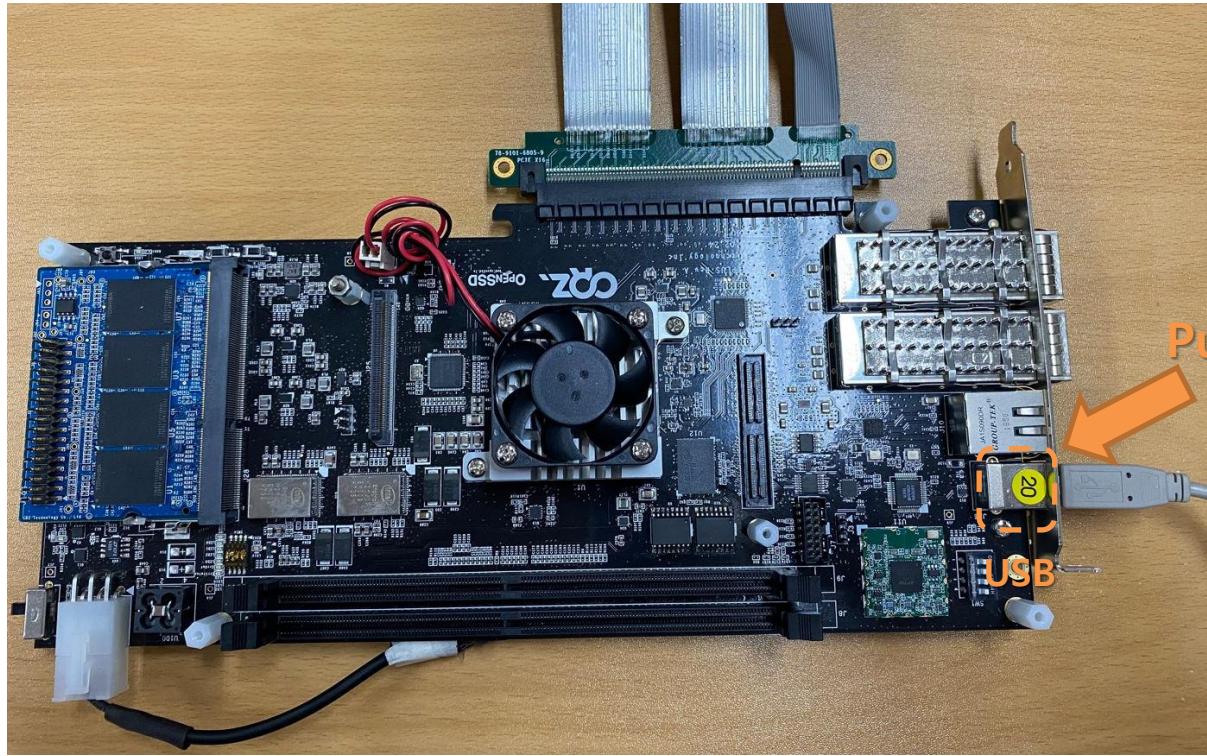


# Connect PCIe Extender



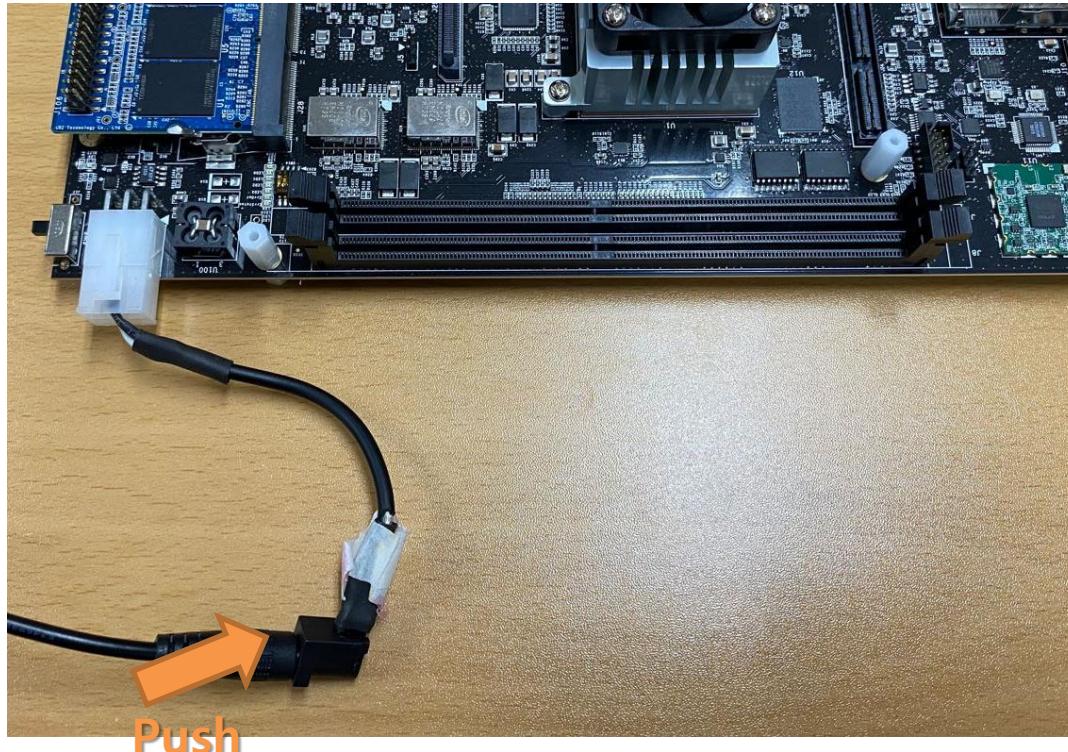
# Connect USB Cable

- USB requires a USB type B (male) to USB type A (male) cable



# Connect Power Cable

- Connect the power cable to the 5.5 mm power connector



# Preparing Software for Development PC

## ■ Download materials

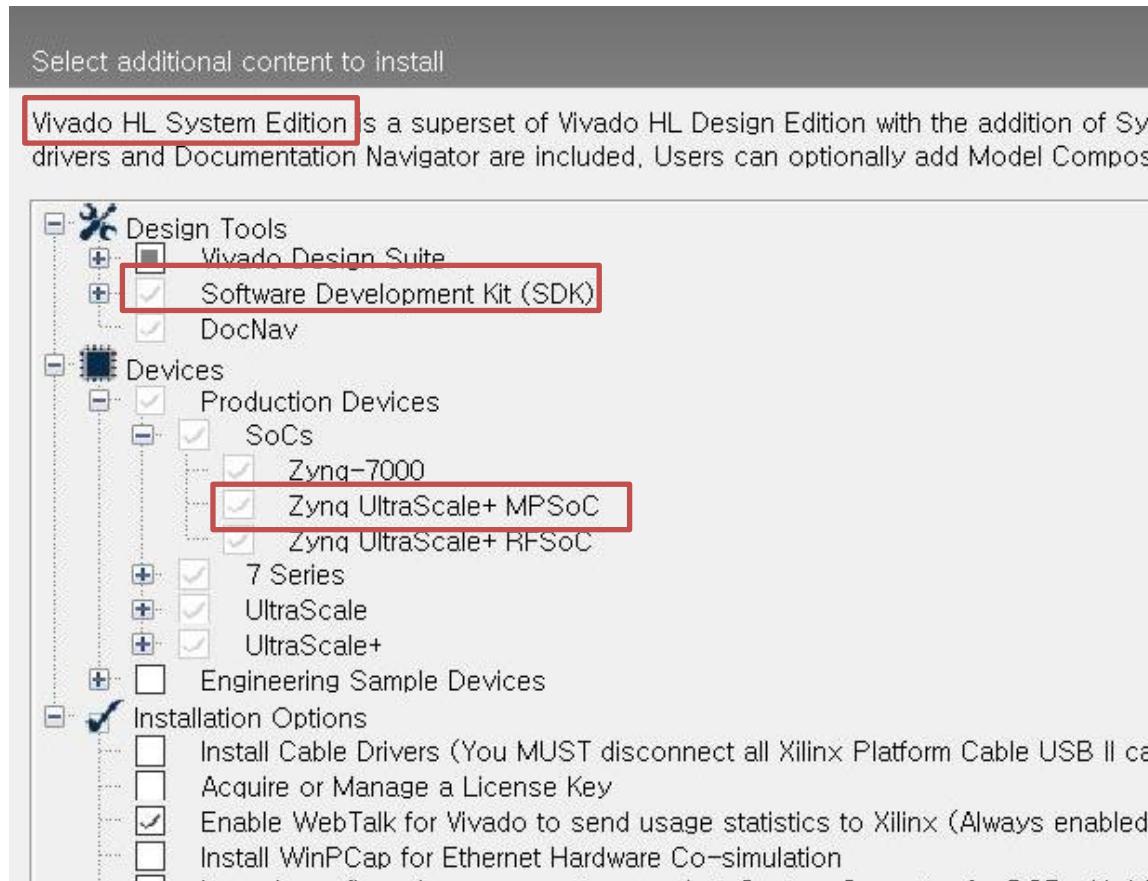
- Pre-defined Vivado project for manual FPGA bitstream generation
- Firmware source code

## ■ Install Xilinx Vivado Design Suite: System Edition 2019.1

- Xilinx Vivado 2019.1
- Xilinx SDK 2019.1

# Install Xilinx Vivado Design Suite

- Make sure that Vivado is HL System Edition and that “Software Development Kit” and “Zynq UltraScale+ MPSoc” are checked



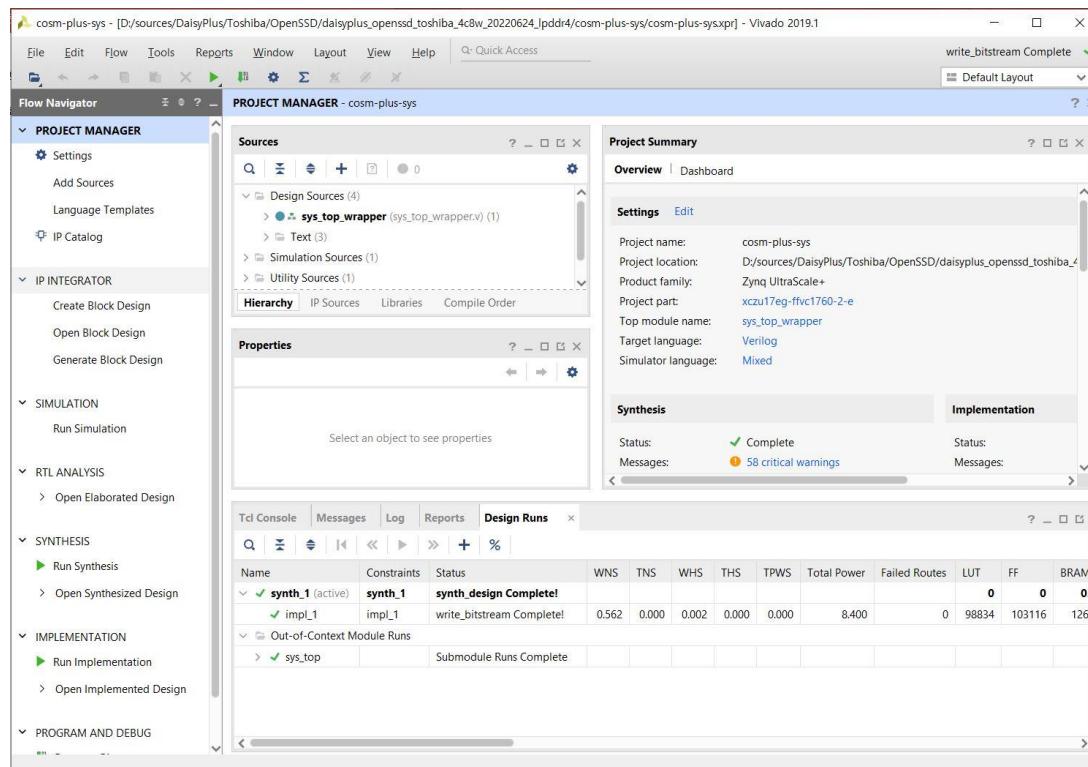
# Generating FPGA Bitstream for Pre-defined Project

- 1. Run synthesis**
- 2. Run implementation**
- 3. Generate bitstream**
- 4. Export hardware**

# Launch Xilinx Vivado

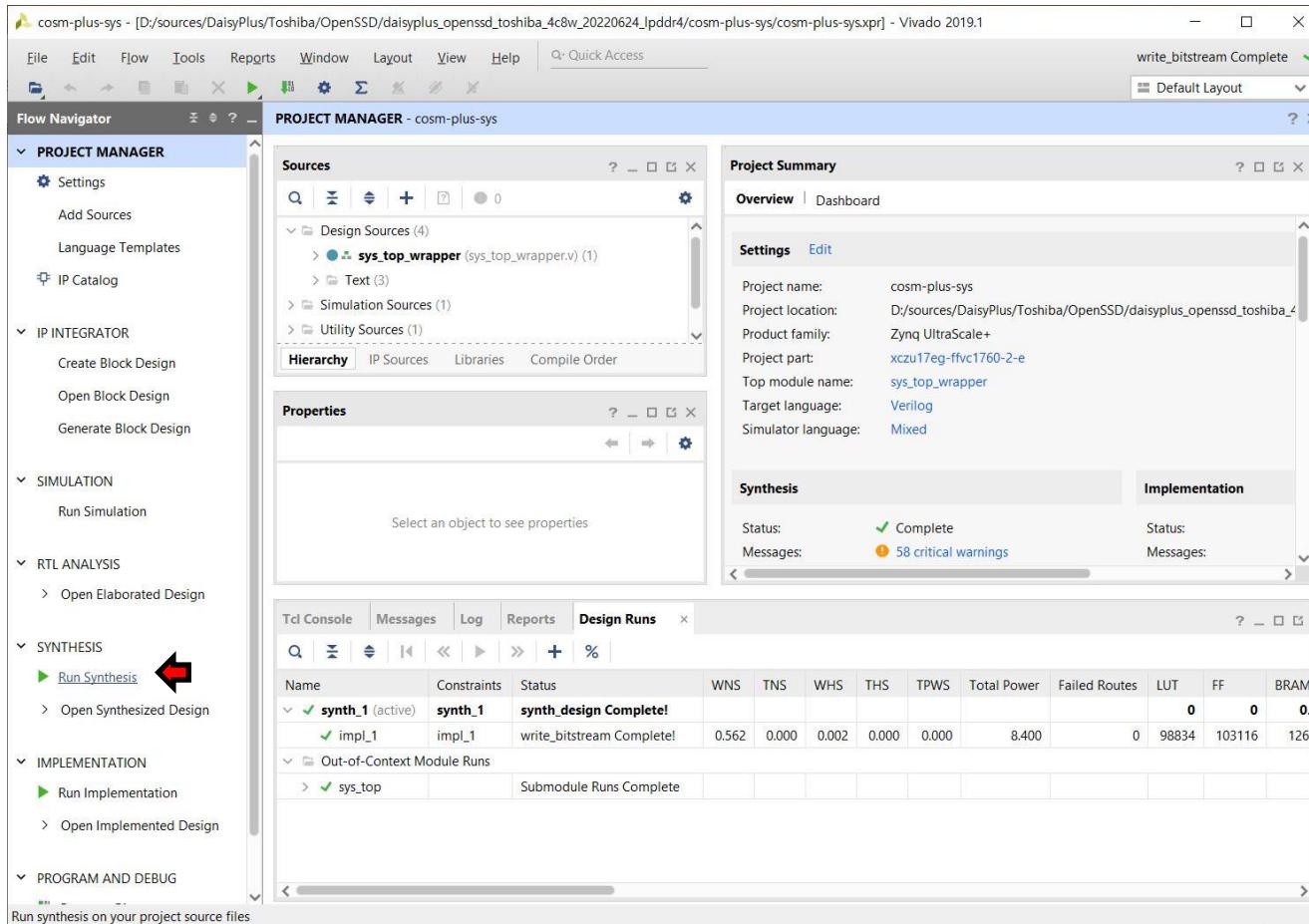
## Open project included in daisyplus\_openssd\_toshiba\_4c8w\_lpddr4

	cosm-plus-sys.sdk	2022-09-30 오후 3:56	파일 폴더
	cosm-plus-sys.srcs	2022-09-30 오후 3:56	파일 폴더
	cosm-plus-sys.xpr	2022-09-30 오후 3:54	XPR 파일 18KB



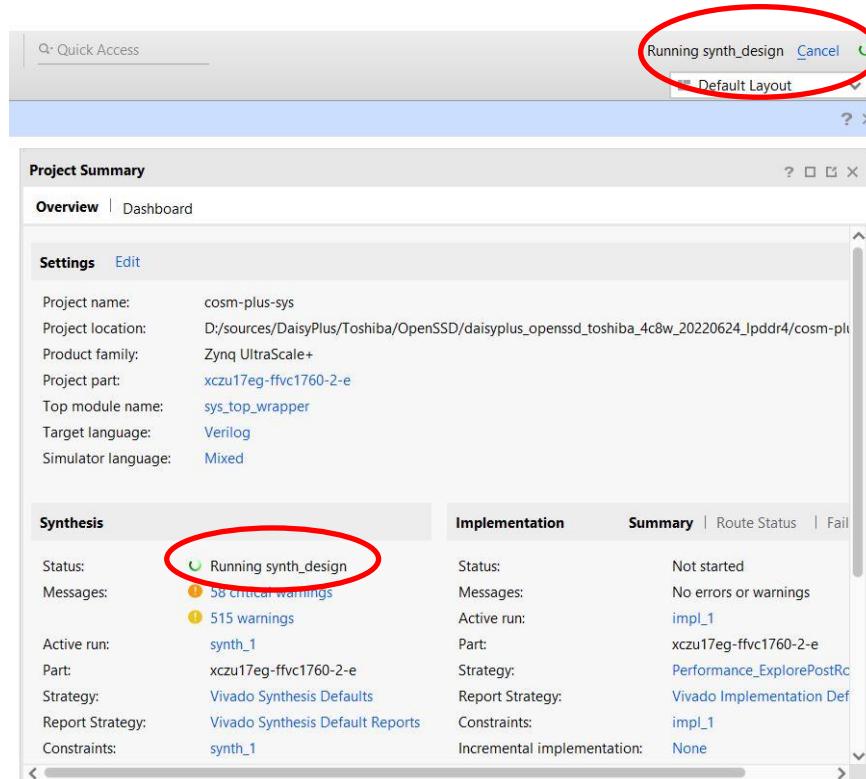
# Run Synthesis (1 / 2)

## Click “Run Synthesis”



# Run Synthesis (2 / 2)

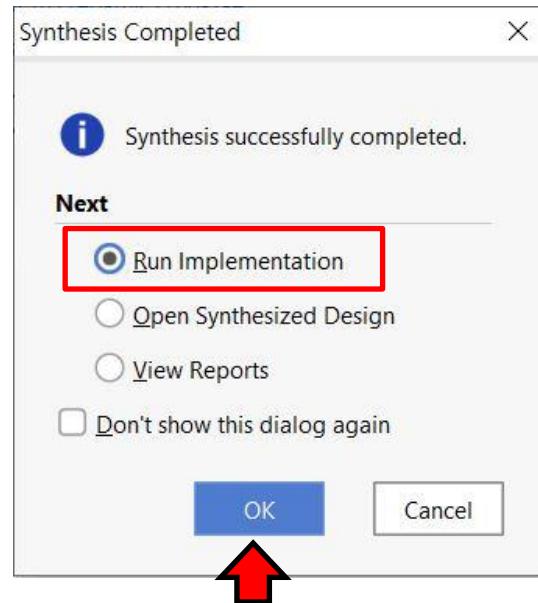
## Synthesis is running...



# Synthesis Complete

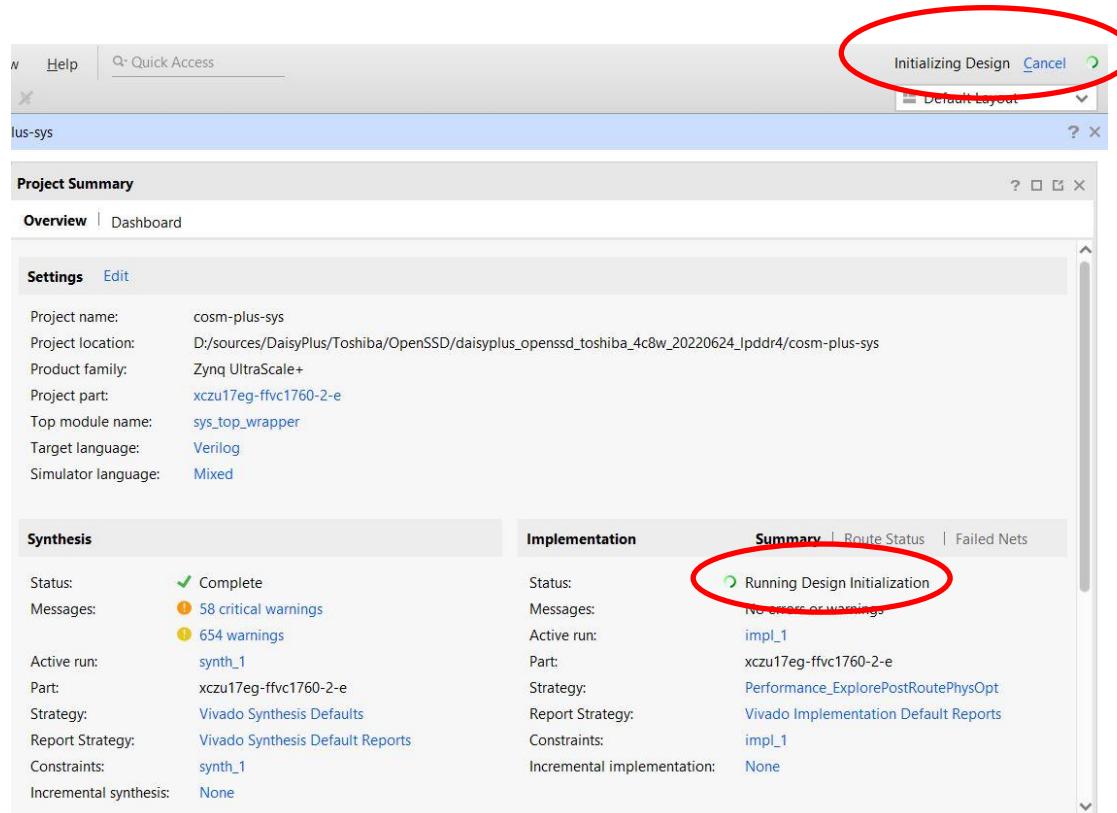
## ■ Select “Run Implementation” and click OK

- If you want to see the synthesized results, choose “Open Synthesized Design” or “View Reports”



# Run Implementation

## Implementation is running...



# Implementation Complete

## Check the status of synthesis and implementation

The screenshot shows the Vivado Project Summary window with the title bar "Implementation Complete" and a green checkmark icon. The window displays project details and synthesis/implementation summaries.

**Project Summary**

**Overview | Dashboard**

**Settings Edit**

**Project name:** cosm-plus-sys  
**Project location:** F:/daisyplus\_openssd\_toshiba\_4c8w\_20220624\_lpddr4/cosm-plus-sys  
**Product family:** Zynq UltraScale+  
**Project part:** xczu17eg-ffvc1760-2-e  
**Top module name:** sys\_top\_wrapper  
**Target language:** Verilog  
**Simulator language:** Mixed

**Synthesis**

Status:	✓ Complete
Messages:	58 critical warnings 654 warnings
Active run:	synth_1
Part:	xczu17eg-ffvc1760-2-e
Strategy:	Vivado Synthesis Defaults
Report Strategy:	Vivado Synthesis Default Reports
Constraints:	synth_1
Incremental synthesis:	None

**Implementation**

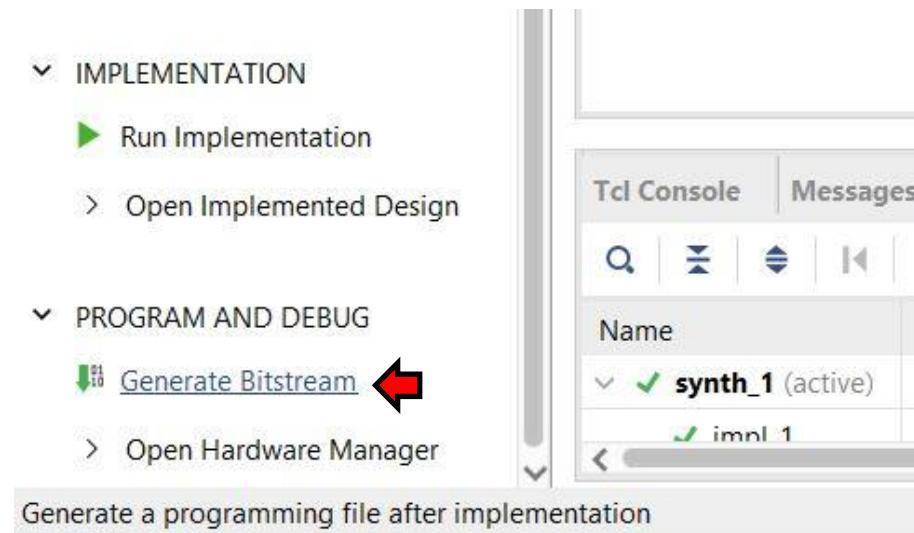
Status:	✓ Complete
Messages:	28 critical warnings 177 warnings
Active run:	impl_1
Part:	xczu17eg-ffvc1760-2-e
Strategy:	Performance_ExplorePostRoutePhysOpt
Report Strategy:	Vivado Implementation Default Reports
Constraints:	impl_1
Incremental implementation:	None

**Summary | Route Status | Failed Nets**

Two red circles highlight the "Complete" status under both the Synthesis and Implementation sections.

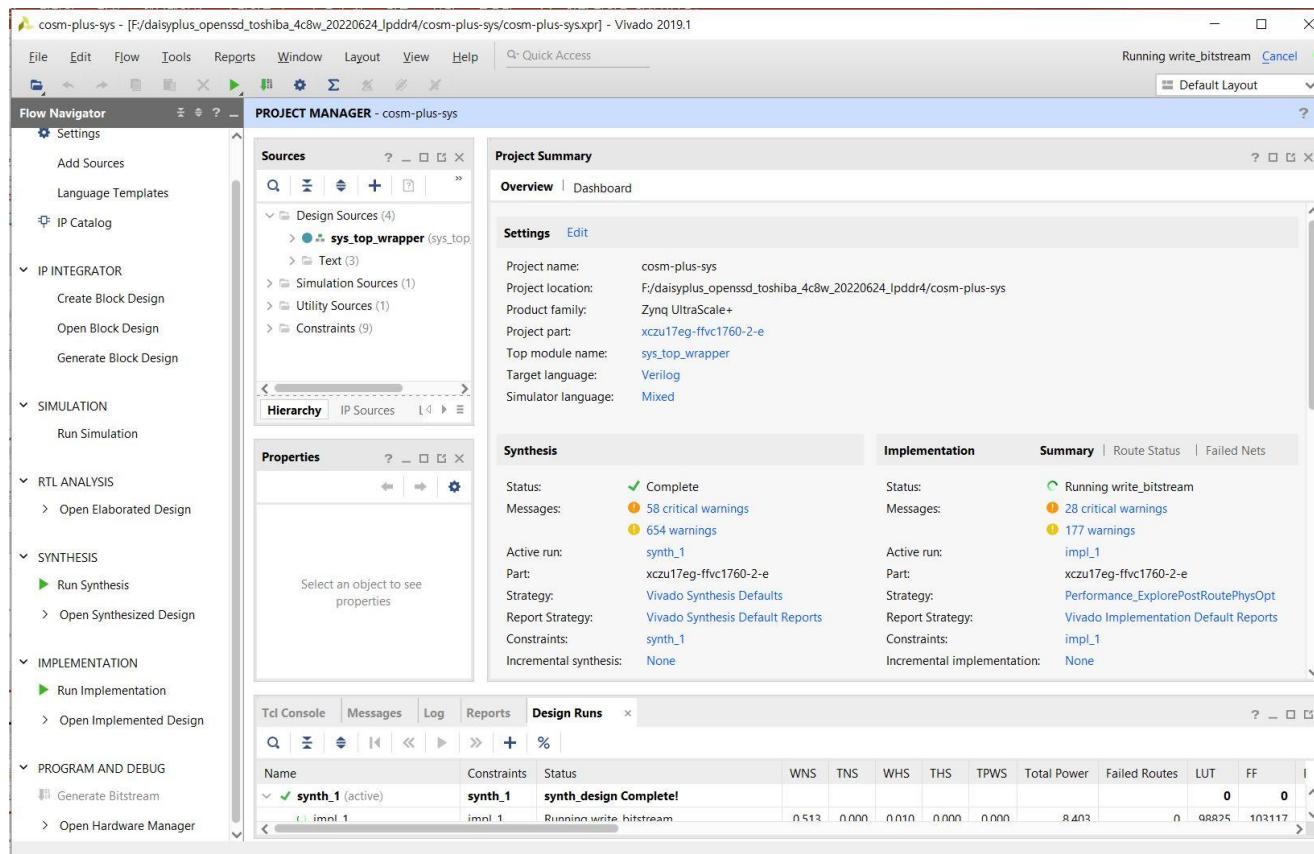
# Generate Bitstream (1 / 2)

## ■ Click “Generate Bitstream”



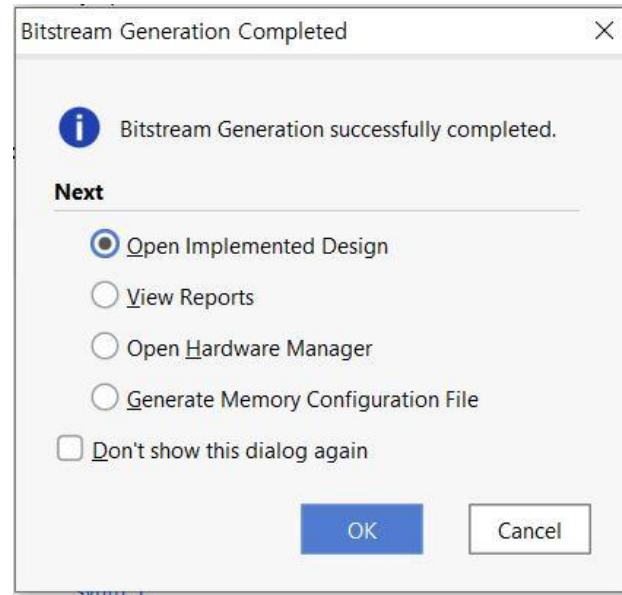
# Generate Bitstream (2 / 2)

## ■ Generate bitstream is running...



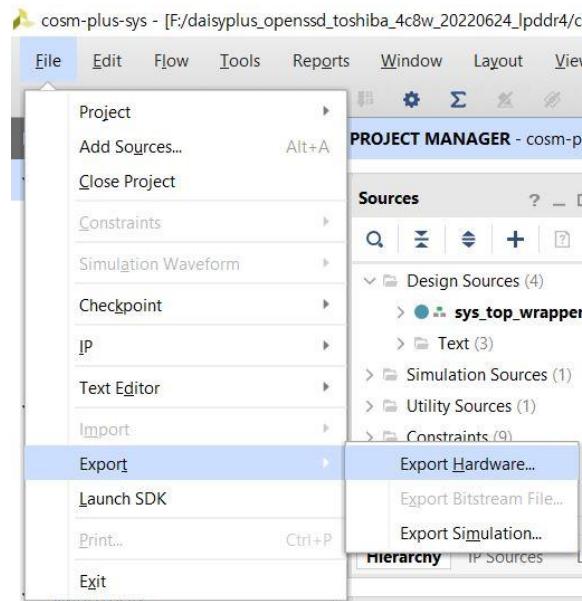
# Bitstream Generation Complete

- If you want to see the implemented design, select open implemented design and click the OK button



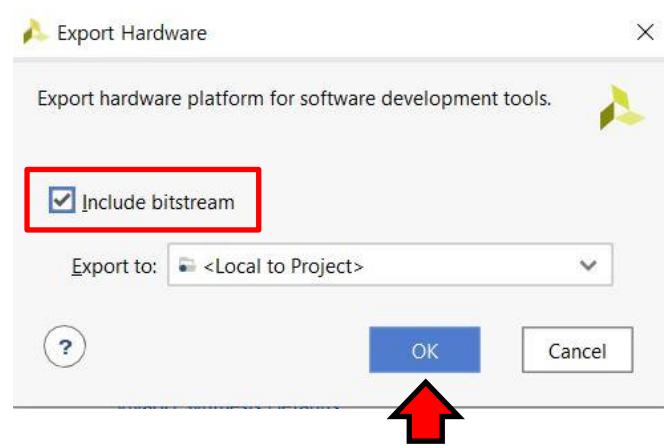
# Export hardware (1 / 2)

- Go to File -> Export and click “Export Hardware”



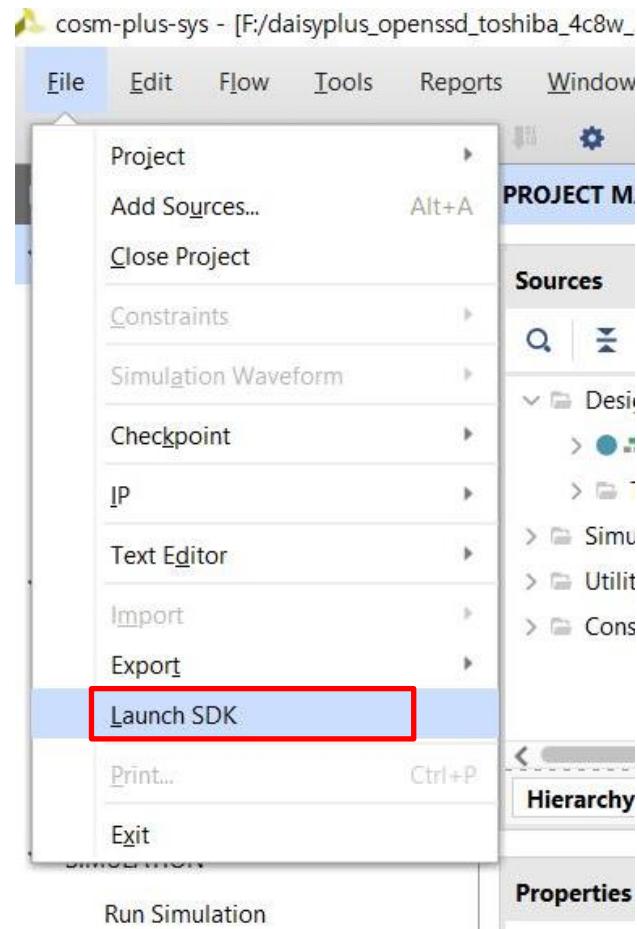
# Export hardware (2 / 2)

- Select the “Include bitstream” and click OK



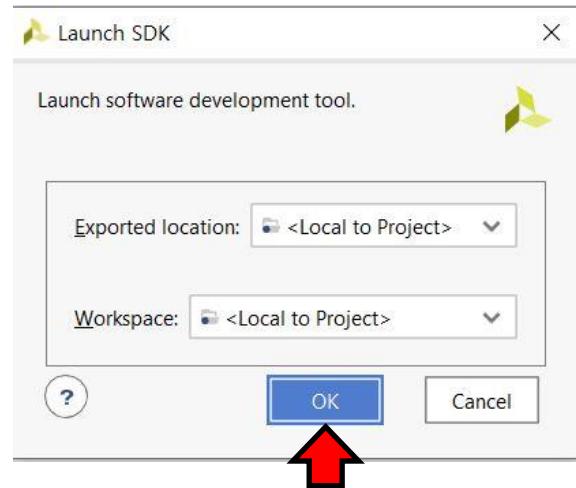
# Launch SDK (1 / 4)

## ■ Go to File -> Launch SDK



# Launch SDK (2 / 4)

## ■ Click the OK button



# Launch SDK (3 / 4)

## Then, SDK is launched

Object Summary

Overview | Dashboard

Settings Edit

Project name:	cosm-plus-sys
Project location:	F:/daisyplus_openssd_toshiba_4c8w_20220624_ipddr4/cosm-plus-sys
Product family:	Zynq UltraScale+
Project part:	xczu17eg-ffvc1760-2-e
Top module name:	sys_top_wrapper
Target language:	Verilog
Simulator language:	

Synthesis

Status:	SDK
Messages:	Software Development Kit

2019.1  
 XILINX.  
Copyright 1986-2019 Xilinx, Inc.  
All Rights Reserved.

Report Strategy: vivado Synthesis Default Reports

Active run:	
Part:	
Strategy:	
Report Strategy:	
Constraints:	synth_1
Incremental synthesis:	None

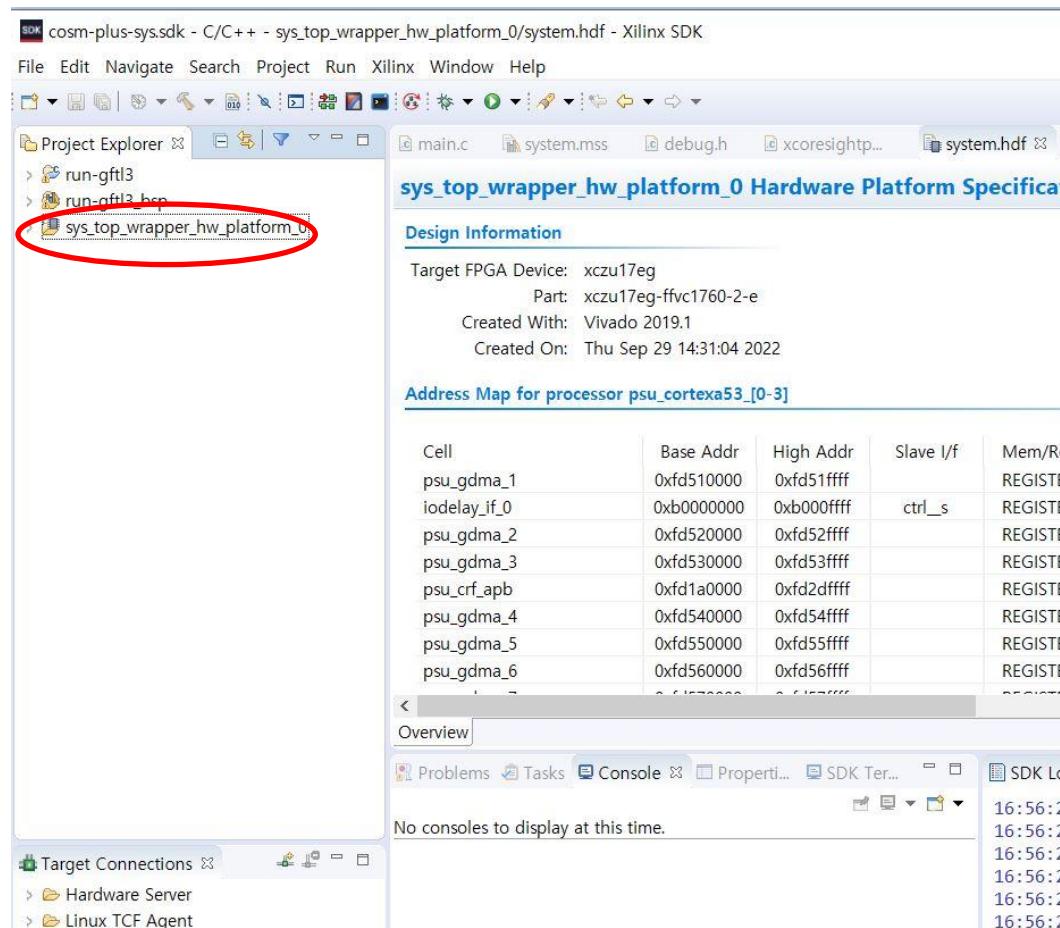
Implementation

Status:	
Messages:	

Active run:  
Part:  
Strategy:  
Report Strat...  
Constraints:  
Incremental i...

# Launch SDK (4 / 4)

As shown below, exported hardware platform is set as target hardware



# Building Firmware for Project

## 1. Build firmware source codes

# Build Firmware (1 / 2)

- If everything goes well, the automatic build process should finish successfully

The screenshot shows a software interface with two main components. At the top is a table with columns for memory addresses and sizes, and rows for various memory regions. Below the table is a terminal window showing the output of a build process. A red oval highlights the terminal output, specifically the command and its results.

psu_pmu_global_0	0xffd80000	0xffdbffff	REGISTER	Non
psu_smmu_gpv	0xfd800000	0xfdffffff	REGISTER	Non
psu_qspi_0	0xff0f0000	0xff0fffff	REGISTER	Non
psu_siou	0xfd3d0000	0xfd3dffff	REGISTER	Non
psu_smmu_reg	0xfd5f0000	0xfd5fffff	REGISTER	Non

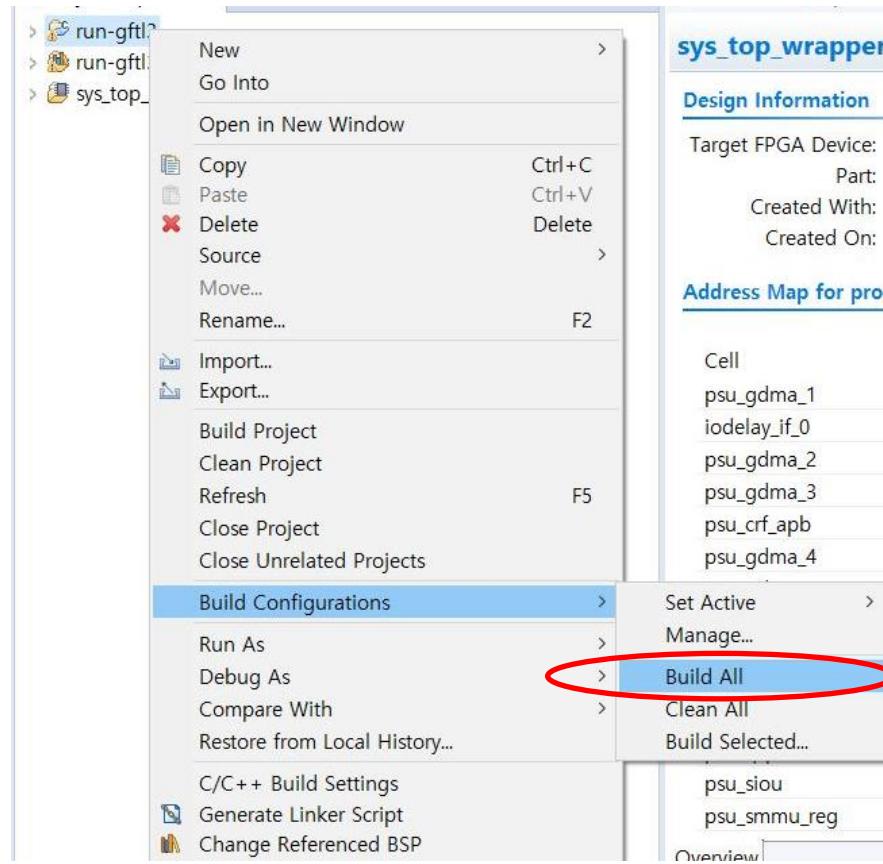
Overview

Problems Tasks Console Properties SDK Terminal

CDT Build Console [run-gftl3]  
aarch64-none-elf-gcc -Wl,-l -Wl,../src/1script.ld -L../../run-gftl3\_bsp/psu\_corte  
'Finished building target: run-gftl3.elf'  
'  
'Invoking: ARM v8 Print Size'  
aarch64-none-elf-size run-gftl3.elf |tee "run-gftl3.elf.size"  
text data bss dec hex filename  
171048 11264 21960 204272 31df0 run-gftl3.elf  
'Finished building: run-gftl3.elf.size'

# Build Firmware (2 / 2)

- Click “Build All” to make both debug and release executables

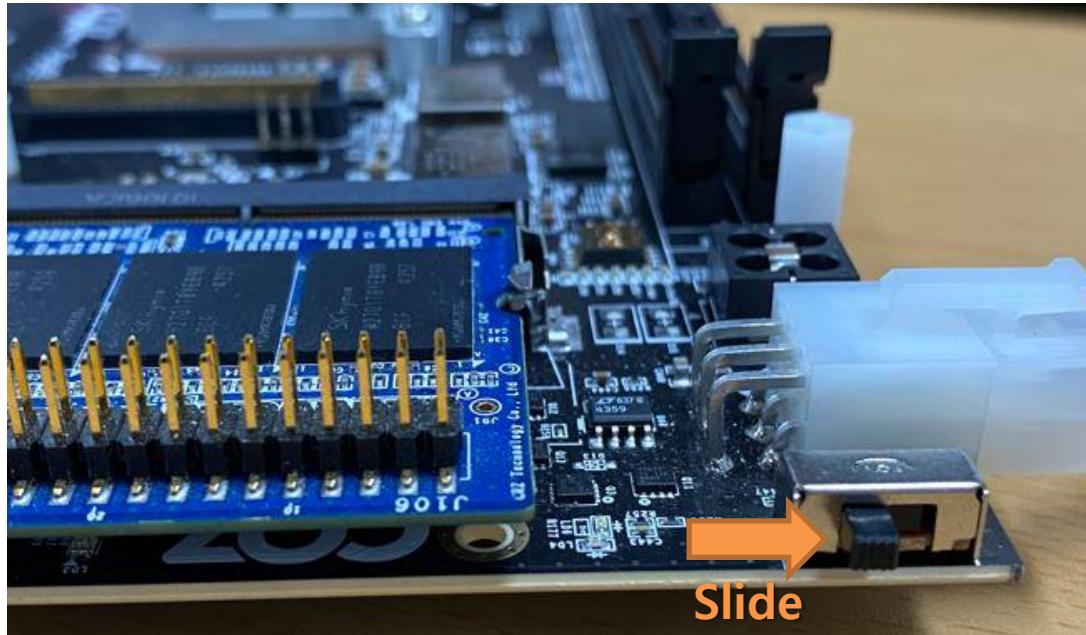


# Preparing for Operating Daisy+ OpenSSD

- 1. Power on the platform board**
- 2. Configure UART**
- 3. Execute firmware**

# Power on the Platform Board

- Before you power on the board, make sure that your host computer is powered off



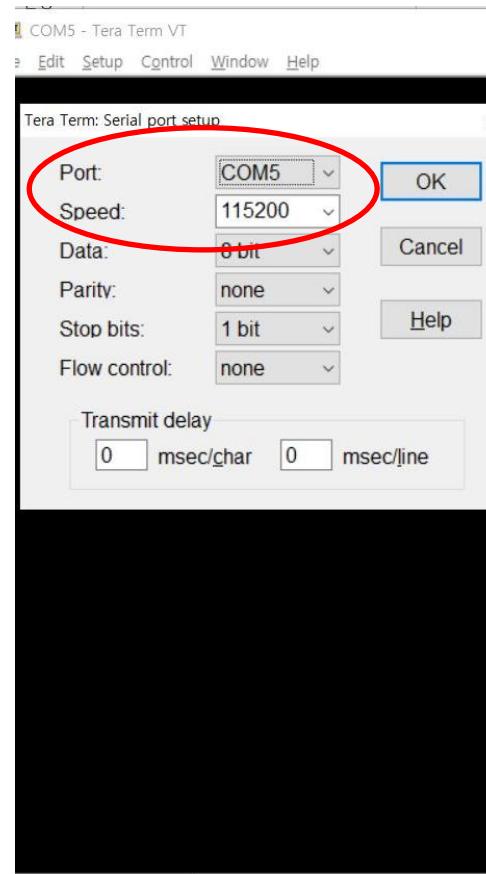
# Configure UART

- Open terminal program.



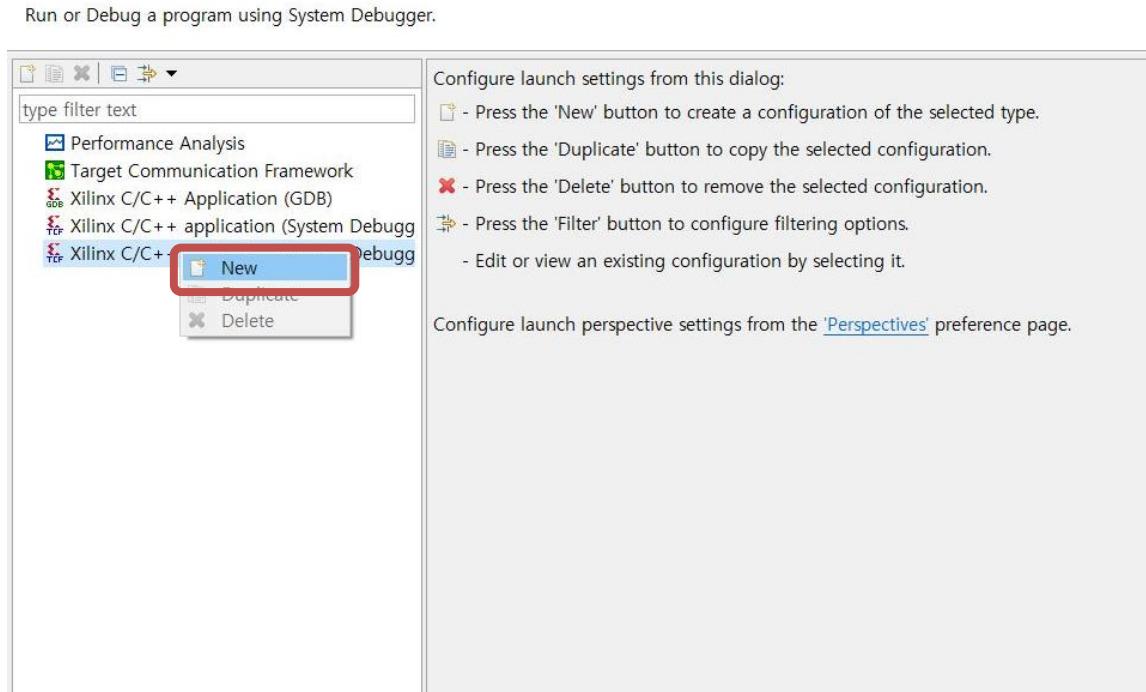
# Configure UART

- On Terminal program, set “Port” and “Baud Rate” to 115200, respectively



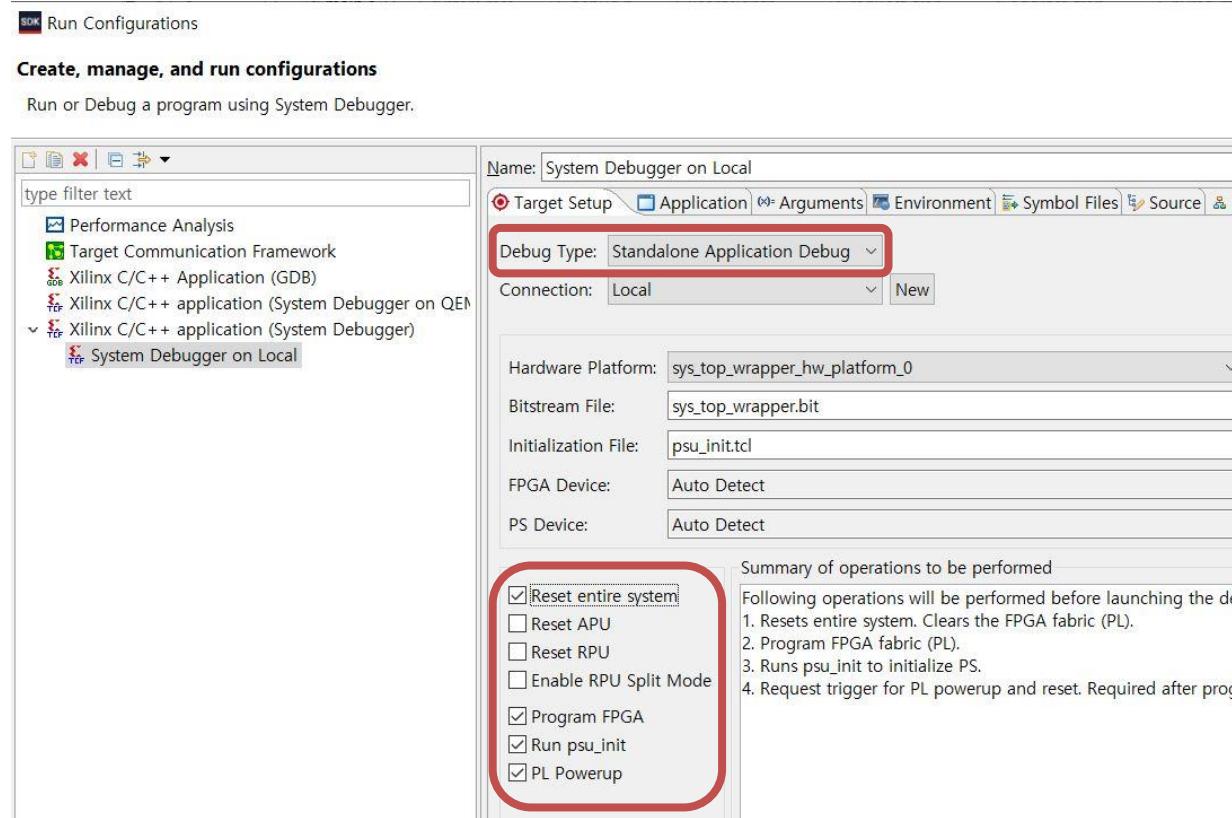
# Execute Firmware (1 / 4)

- Click “Run” -> “Run Configurations” and right-click on “Xilinx C/C++ application(System Debugger) and click “New”.



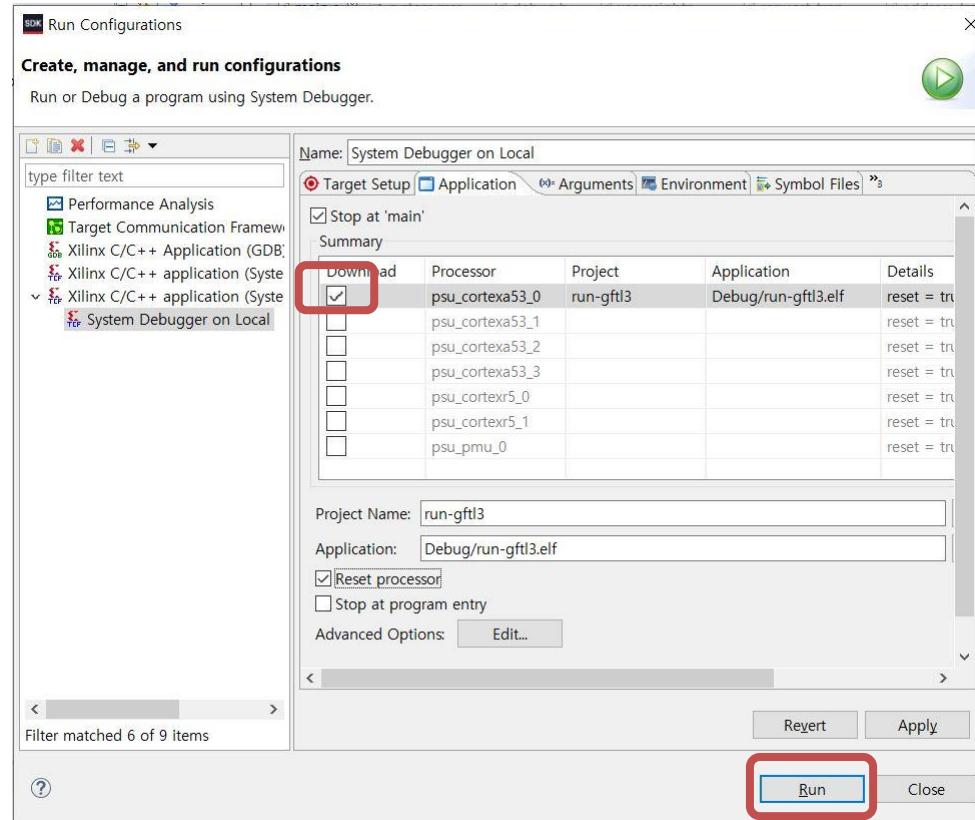
# Execute Firmware (2 / 4)

- On “Target Setup” tab, select “Standalone Application Debug” as “Debug Type” and check “Reset entire system”.



# Execute Firmware (3 / 4)

- On “Application” tab, check “psu\_cortexa53\_0” and click “Run”.



# Execute Firmware (4 / 4)

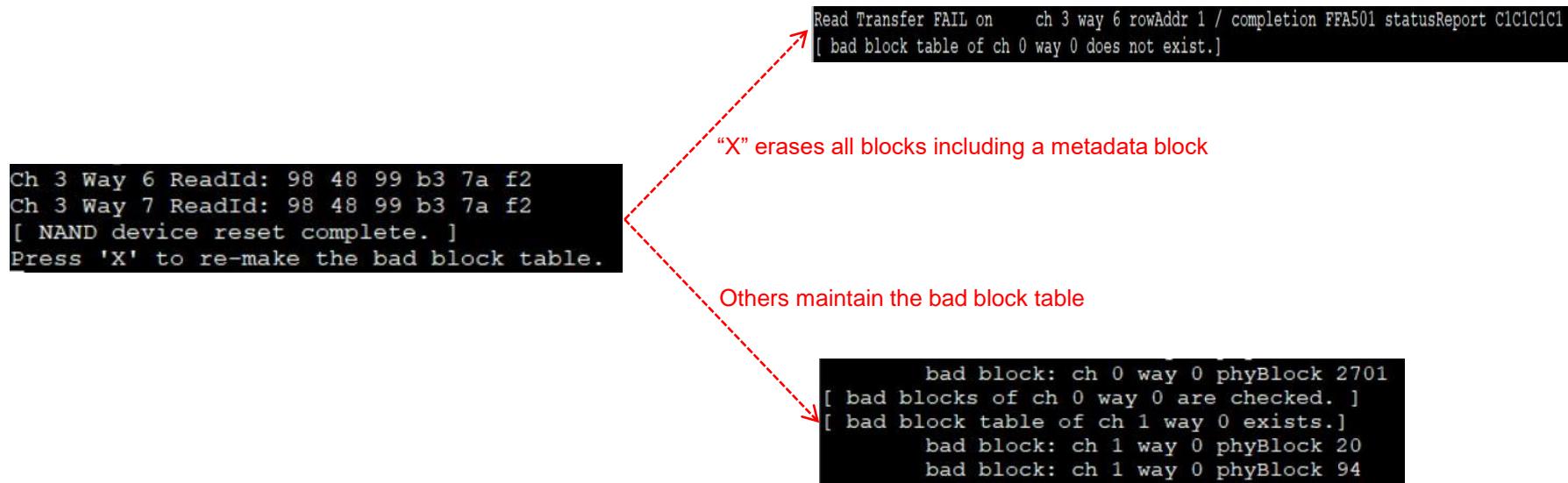
- Press 'n' to maintain the bad block table

```
VT COM5 - Tera Term VT
File Edit Setup Control Window Help
Ch 1 Way 7 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 0 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 1 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 2 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 3 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 4 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 5 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 6 ReadId: 98 48 99 b3 7a f2
Ch 2 Way 7 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 0 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 1 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 2 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 3 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 4 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 5 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 6 ReadId: 98 48 99 b3 7a f2
Ch 3 Way 7 ReadId: 98 48 99 b3 7a f2
[ NAND device reset complete. ]
Press 'X' to re-make the bad block table.
```

# Bad Block Management (1 / 2)

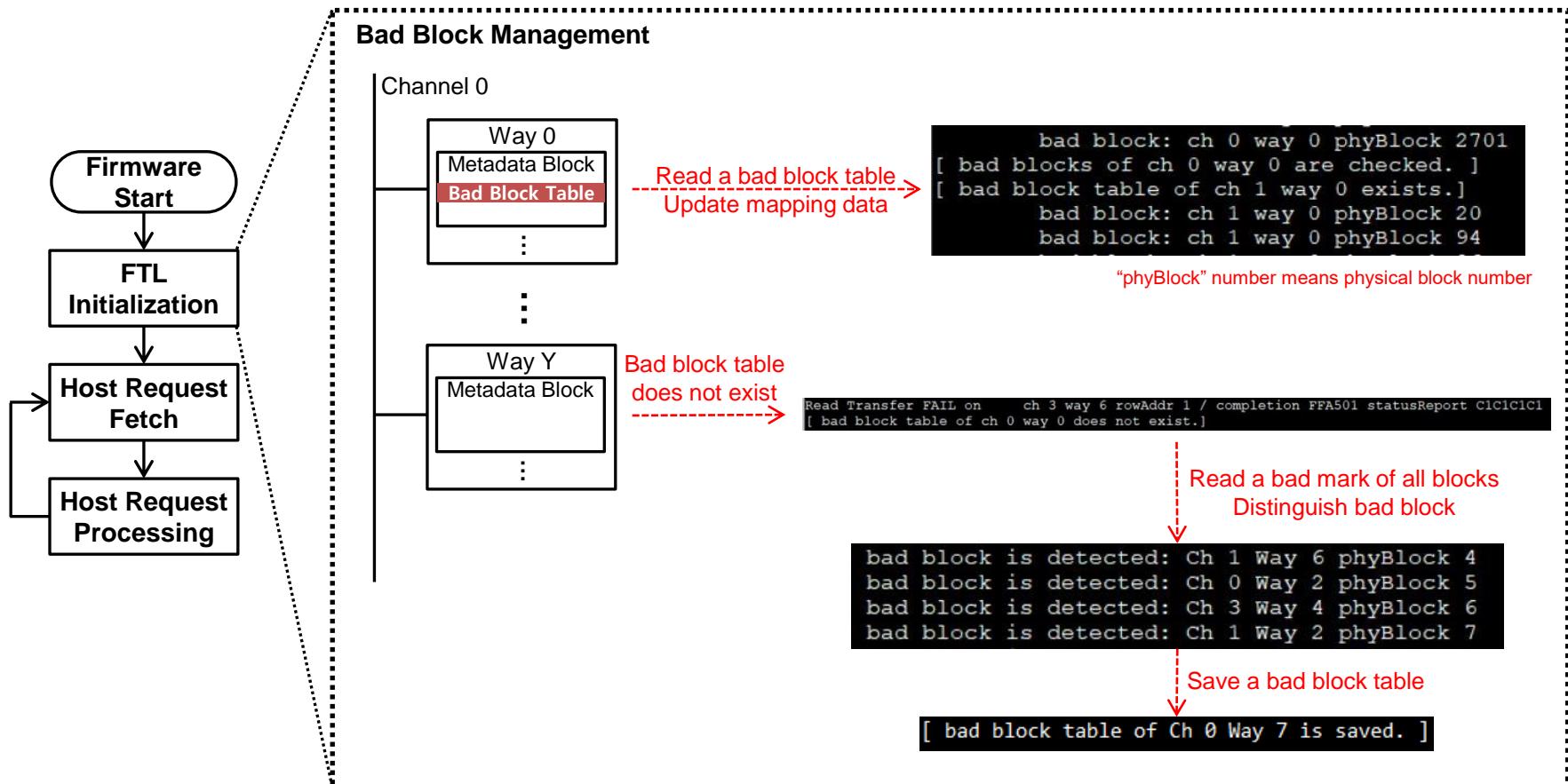
## ■ Choose whether remake the bad block table in FTL initialization step

- If you want to remake the bad block table, press “X” on UART terminal
  - Damaged bad block table can be recovered



# Bad Block Management (2 / 2)

## Bad blocks are detected in FTL initialization step



# Turn on the Host PC

- Turn on the host PC when the firmware reset is done

```
        bad block: ch 3 way 7 phyBlock 2740
[ bad blocks of ch 3 way 7 are checked. ]
Bad block remapping start...
Bad block remapping end
Erase User block space...wait for a minute..
Done.
[ storage capacity 235804 MB ]
[ ftl configuration complete. ]

FTL reset complete!!!
Turn on the host PC
```

# UART Messages While Host Computer is Booting up

- NVMe SSD initialization steps are on going

```
FTL reset complete!!!
Turn on the host PC
PCIe Link: 1
PCIe Bus Master: 1
PCIe Bus Master: 0
PCIe Bus Master: 1
NVME CC.EN: 1

NVMe ready!!!
Create IO CQ, DW11: 0x00000001, DW10: 0x00010001
Create IO SQ, DW11: 0x00010001, DW10: 0x00010001
PCIe IRQ Disable: 0
PCIe IRQ Disable: 1
PCIe IRQ Disable: 0
PCIe MSI Enable: 1, 0x0
NVME CC.EN: 0

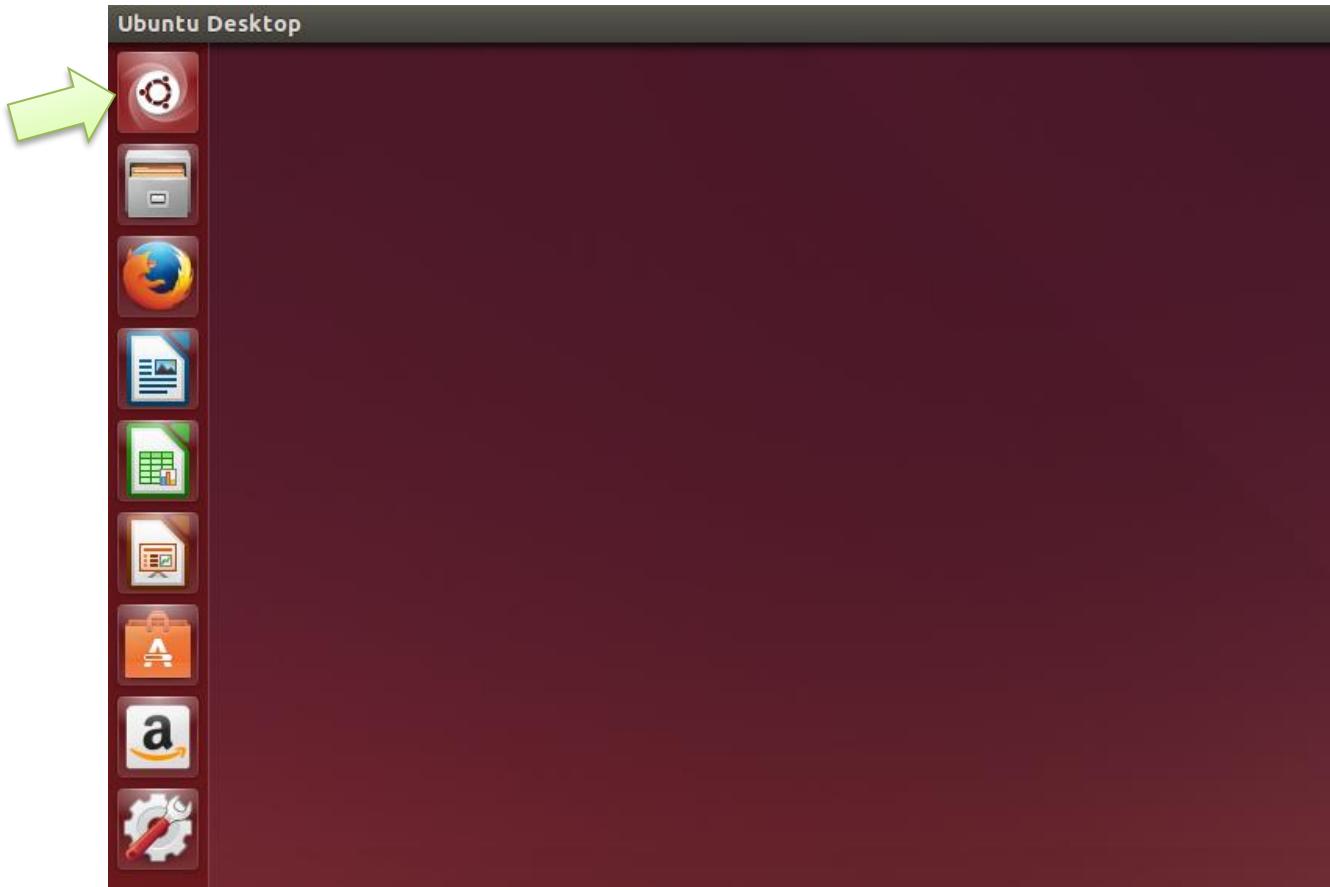
NVMe disable!!!
```

# Operating Daisy+ OpenSSD (Linux)

- 1. Check device recognition**
- 2. Create a partition**
- 3. Check the created partition**
- 4. Format the partition**
- 5. Create a mount point**
- 6. Mount the partition**
- 7. Check the mounted partition**

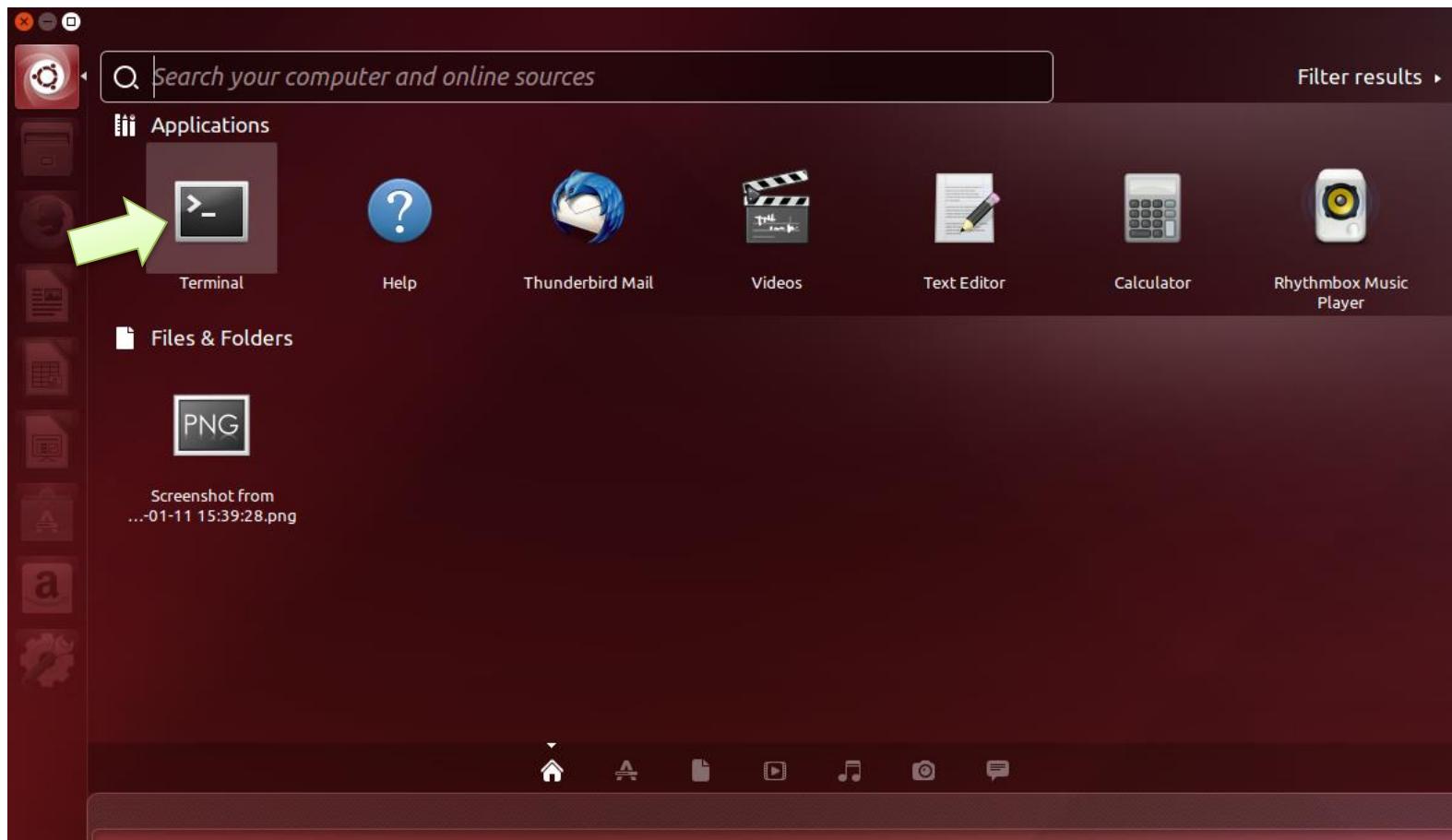
# Open a Terminal (1 / 2)

- Click the pointed icon



# Open a Terminal (2 / 2)

## ■ Click the terminal icon



# Check Device Recognition (1 / 2)

- Types “lspci” -> press ENTER -> check “Non-Volatile memory controller: Xilinx Corporation Device 901f” on the PCI device list

```
hgchoe@ubuntu:~$ lspci
00:00.0 Host bridge: Intel Corporation Xeon E3-1200 v6/7th Gen Core Processor Host Bridge
00:01.0 PCI bridge: Intel Corporation Xeon E3-1200 v5/E3-1500 v5/6th Gen Core Processor PCI Express Root Port #4
00:02.0 VGA compatible controller: Intel Corporation HD Graphics 630 (rev 04)
00:14.0 USB controller: Intel Corporation 200 Series/Z370 Chipset Family USB 3.0 xHCI Controller
00:14.2 Signal processing controller: Intel Corporation 200 Series PCH Thermal Subsystem
00:16.0 Communication controller: Intel Corporation 200 Series PCH CSME HECI #1
00:17.0 SATA controller: Intel Corporation 200 Series PCH SATA controller [AHCI mode]
00:1c.0 PCI bridge: Intel Corporation 200 Series PCH PCI Express Root Port #5 (rev f0)
00:1f.0 ISA bridge: Intel Corporation 200 Series PCH LPC Controller (H270)
00:1f.2 Memory controller: Intel Corporation 200 Series/Z370 Chipset Family Power Management Controller
00:1f.3 Audio device: Intel Corporation 200 Series PCH HD Audio
00:1f.4 SMBus: Intel Corporation 200 Series/Z370 Chipset Family SMBus Controller
01:00.0 Non-Volatile memory controller: Xilinx Corporation Device 901f
02:00.0 Ethernet controller: Realtek Semiconductor Co., Ltd. RTL8111/8168/8411 PCI Express Gigabit Ethernet Controller
hgchoe@ubuntu:~$
```

# Check Device Recognition (2 / 2)

- Types “ls /dev” -> press ENTER -> check “nvme0n1” on the device list

```
hgchoe@ubuntu:~$ ls /dev
autofs          loop
block           loop-control
bsg             loop0
btrfs-control   loop1
bus              loop10
cdrom            loop11
cdrw             loop12
char              loop13
console          loop14
core              loop15
cpu_dma_latency  loop16
cuse              loop17
disk              loop18
dma_heap          loop19
dri               loop2
drm_dp_aux0      loop20
drm_dp_aux1      loop21
dvd               loop22
dvdrw             loop23
ecryptfs          loop24
initctl           loop25
input             loop26
kmsg              loop27
kvm               loop28
log               loop29
loop-control
loop5
loop6
loop7
loop8
loop9
mapper
mcelog
mei0
mem
mqueue
net
ng0n1
null
nvme0
nvme0n1
nvram
port
ppp
psaux
ptmx
pts
random
rfkill
rtc
rtc0
sda
sda1
sda2
sda3
sda4
sda5
sdb
sdb1
sdb2
sdb3
sg0
sg1
sg2
shm
snapshot
hgchoe@ubuntu:~$
```

# Create a Partition

- Type “`sudo fdisk /dev/nvme0n1`”, press ENTER -> type your password, press ENTER -> type “`n`”, press ENTER->press ENTER->press ENTER, press ENTER -> type “`w`”, press ENTER

```
hgchoe@ubuntu:~$ sudo fdisk /dev/nvme0n1
[sudo] password for hgchoe:

Welcome to fdisk (util-linux 2.31.1).
Changes will remain in memory only, until you decide to write them.
Be careful before using the write command.

Device does not contain a recognized partition table.
Created a new DOS disklabel with disk identifier 0xbf7cc307.

Command (m for help): n
Partition type
  p  primary (0 primary, 0 extended, 4 free)
  e  extended (container for logical partitions)
Select (default p):

Using default response p.
Partition number (1-4, default 1):
First sector (256-60365823, default 256):
Last sector, +sectors or +size{K,M,G,T,P} (256-60365823, default 60365823):

Created a new partition 1 of type 'Linux' and of size 230.3 GiB.

Command (m for help): w
The partition table has been altered.
Calling ioctl() to re-read partition table.
Syncing disks.

hgchoe@ubuntu:~$
```

# Check the Created Partition

- Types “ls /dev” -> press ENTER -> check “nvme0n1p1” on the device list

```
hgchoe@ubuntu:~$ ls /dev
autofs          i2c-4
block           initctl
bsg             input
btrfs-control   kmsg
bus              kvm
cdrom           log
cdrw            loop0
char             loop1
console          loop10
core             loop11
cpu_dma_latency loop12
cuse             loop13
disk             loop14
dma_heap         loop15
dri              loop16
drm_dp_aux0     loop17
drm_dp_aux1     loop18
mem              mqueue
net              ng0n1
null             nvme0
nvme0n1          nvme0n1
nvme0n1p1        nvme0n1p1
nvram            port
ppp              pts
psaux            ptmx
random           rfkill
rtc              sr0
stderr           stdin
stdout           tpm0
tty               tty0
tty1              nvme0n1p1
tty34            tty1
tty35            tty2
tty36            tty3
tty37            tty4
tty38            tty5
tty39            tty6
tty40            tty7
tty41            tty8
tty42            tty9
tty43            tty10
tty44            tty11
tty45            tty12
tty46            tty13
tty47            tty14
tty48            tty15
tty49            tty16
tty50            tty17
tty51            tty18
tty52            tty19
tty53            tty20
tty54            tty21
tty55            tty22
tty56            tty23
tty57            tty24
tty58            tty25
tty59            tty26
tty60            tty27
tty61            tty28
tty62            tty29
tty63            tty30
tty64            tty31
tty65            tty32
tty66            tty33
tty67            tty34
tty68            tty35
tty69            tty36
tty70            tty37
tty71            tty38
tty72            tty39
tty73            tty40
tty74            tty41
tty75            tty42
tty76            tty43
tty77            tty44
tty78            tty45
tty79            tty46
tty80            tty47
tty81            tty48
tty82            tty49
tty83            tty50
tty84            tty51
tty85            tty52
tty86            tty53
tty87            tty54
tty88            tty55
tty89            tty56
tty90            tty57
tty91            tty58
tty92            tty59
tty93            tty60
tty94            tty61
tty95            tty62
tty96            tty63
tty97            tty64
tty98            tty65
tty99            tty66
ttyS0            tty67
ttyS1            tty68
ttyS2            tty69
ttyS3            tty70
ttyS4            tty71
ttyS5            tty72
ttyS6            tty73
ttyS7            tty74
ttyS8            tty75
ttyS9            tty76
ttyS10           tty77
ttyS11           tty78
ttyS12           tty79
ttyS13           tty80
ttyS14           tty81
ttyS15           tty82
ttyS16           tty83
ttyS17           tty84
ttyS18           tty85
ttyS19           tty86
ttyS20           tty87
ttyS21           tty88
ttyS22           tty89
ttyS23           tty90
ttyS24           tty91
ttyS25           tty92
ttyS26           tty93
ttyS27           tty94
ttyS28           tty95
ttyS29           tty96
ttyS30           tty97
ttyS31           tty98
ttyS32           tty99
udmabuf         uhid
uinput          urandom
usb              userio
vcs              vcs1
vcs1            vcs2
vcs2            vcs3
vcs3            vcs4
vcs4            vcs5
vcs5            vcs6
vcs6            vcsa
vcsa            vcsa1
vcsa1           vcsa2
```

# Format the Partition

- Type “**sudo mkfs -t ext4 / dev/nvme0n1p1**”, press **ENTER**

```
hgchoe@ubuntu:~$ sudo mkfs -t ext4 /dev/nvme0n1p1
mke2fs 1.44.1 (24-Mar-2018)
Creating filesystem with 60365568 4k blocks and 15097856 inodes
Filesystem UUID: 4c5f1175-5c68-459d-b516-558811bc19ca
Superblock backups stored on blocks:
            32768, 98304, 163840, 229376, 294912, 819200, 884736, 1605632, 2654208,
            4096000, 7962624, 11239424, 20480000, 23887872

Allocating group tables: done
Writing inode tables: done
Creating journal (262144 blocks): done
Writing superblocks and filesystem accounting information: done

hgchoe@ubuntu:~$
```

# Create a Mount Point

- Type “**sudo mkdir /media/nvme**”, press ENTER

```
hgchoe@ubuntu:~$ sudo mkdir /media/nvme
```

# Mount the Partition

- Type “**sudo mount /dev/nvme0n1p1 /media/nvme**”, press ENTER

```
hgchoe@ubuntu:~$ sudo mount /dev/nvme0n1p1 /media/nvme  
hgchoe@ubuntu:~$
```

# Check the Mounted Partition (1 / 2)

- Type “lsblk”, press ENTER -> check the mounted partition on the block device list

```
hgchoe@ubuntu:~$ lsblk
NAME   MAJ:MIN RM  SIZE RO TYPE MOUNTPOINT
loop0    7:0    0  70.4M  1 loop /snap/core22/275
loop1    7:1    0   556K  1 loop /snap/gnome-logs/112
loop2    7:2    0   1.5M  1 loop /snap/gnome-system-monitor/181
loop3    7:3    0   476K  1 loop /snap/gnome-characters/781
loop4    7:4    0   48M   1 loop /snap/snapd/17029
loop5    7:5    0   48M   1 loop /snap/snapd/17336
loop6    7:6    0  219M  1 loop /snap/gnome-3-34-1804/72
loop7    7:7    0  63.2M  1 loop /snap/core20/1623
loop8    7:8    0  55.6M  1 loop /snap/core18/2560
loop9    7:9    0 346.3M  1 loop /snap/gnome-3-38-2004/115
loop10   7:10   0   2.6M  1 loop /snap/gnome-calculator/920
loop11   7:11   0   81.3M  1 loop /snap/gtk-common-themes/1534
loop12   7:12   0   704K  1 loop /snap/gnome-characters/741
loop13   7:13   0 346.3M  1 loop /snap/gnome-3-38-2004/119
loop14   7:14   0   4K   1 loop /snap/bare/5
loop15   7:15   0   696K  1 loop /snap/gnome-logs/115
loop16   7:16   0  219M  1 loop /snap/gnome-3-34-1804/77
loop17   7:17   0 414.4M  1 loop /snap/gnome-42-2204/29
loop18   7:18   0   2.6M  1 loop /snap/gnome-system-monitor/178
loop19   7:19   0   2.5M  1 loop /snap/gnome-calculator/884
loop20   7:20   0  55.6M  1 loop /snap/core18/2566
loop21   7:21   0  91.7M  1 loop /snap/gtk-common-themes/1535
loop22   7:22   0   62M   1 loop /snap/core20/1611
sda      8:0    0 953.9G  0 disk
└─sda1   8:1    0   499M  0 part
└─sda2   8:2    0   100M  0 part /boot/efi
└─sda3   8:3    0   16M   0 part
└─sda4   8:4    0 952.7G  0 part
└─sda5   8:5    0   568M  0 part
sdb      8:16   0 931.5G  0 disk
└─sdb1   8:17   0   512M  0 part
└─sdb2   8:18   0 899.1G  0 part /
└─sdb3   8:19   0   31.9G  0 part
sr0     11:0   1 1024M  0 rom
nvme0n1  259:0   0 230.3G  0 disk
└─nvme0n1p1 259:2   0 230.3G  0 part /media/nvme
hgchoe@ubuntu:~$
```

# Check the Mounted Partition (2 / 2)

- Type “df -h”, press ENTER -> check the mounted partition on the storage list

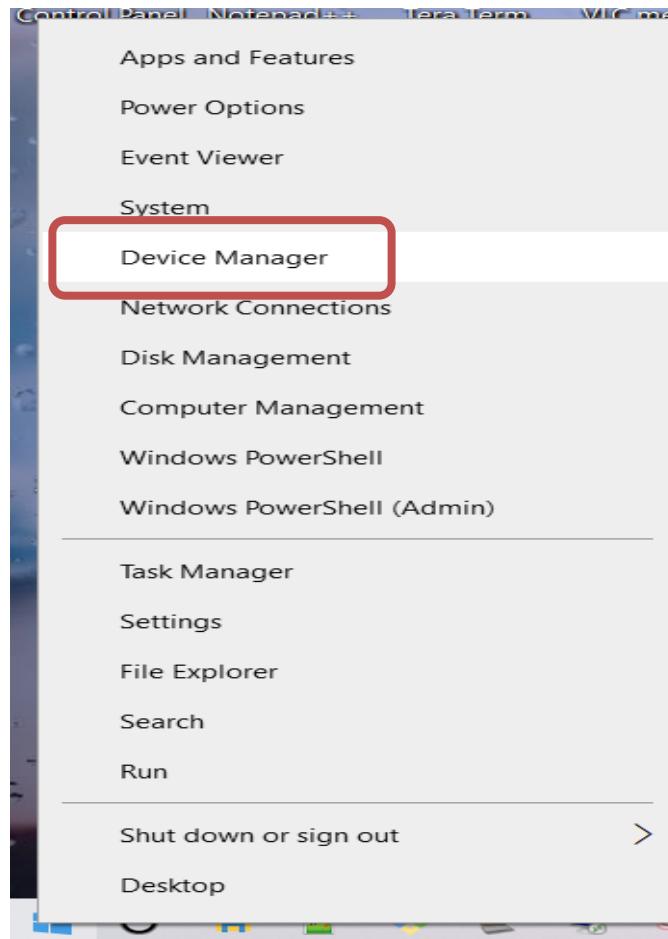
```
hgchoe@ubuntu:~$ df -h
Filesystem      Size  Used  Avail Use% Mounted on
udev            16G    0    16G   0% /dev
tmpfs           3.2G  3.6M  3.2G   1% /run
/dev/sdb2        884G  452G  388G  54% /
tmpfs           16G    0    16G   0% /dev/shm
tmpfs           5.0M  4.0K  5.0M   1% /run/lock
tmpfs           16G    0    16G   0% /sys/fs/cgroup
/dev/loop0       71M   71M    0 100% /snap/core22/275
/dev/loop1       640K  640K   0 100% /snap/gnome-logs/112
/dev/loop2       1.5M  1.5M   0 100% /snap/gnome-system-monitor/181
/dev/loop3       512K  512K   0 100% /snap/gnome-characters/781
/dev/loop4       48M   48M   0 100% /snap/snapd/17029
/dev/loop6       219M  219M   0 100% /snap/gnome-3-34-1804/72
/dev/loop5       48M   48M   0 100% /snap/snapd/17336
/dev/loop8       56M   56M   0 100% /snap/core18/2560
/dev/loop7       64M   64M   0 100% /snap/core20/1623
/dev/loop10      2.7M  2.7M   0 100% /snap/gnome-calculator/920
/dev/loop12      768K  768K   0 100% /snap/gnome-characters/741
/dev/loop15      768K  768K   0 100% /snap/gnome-logs/115
/dev/loop11      82M   82M   0 100% /snap/gtk-common-themes/1534
/dev/loop16      219M  219M   0 100% /snap/gnome-3-34-1804/77
/dev/loop13      347M  347M   0 100% /snap/gnome-3-38-2004/119
/dev/loop14      128K  128K   0 100% /snap/bare/5
/dev/loop17      415M  415M   0 100% /snap/gnome-42-2204/29
/dev/loop9       347M  347M   0 100% /snap/gnome-3-38-2004/115
/dev/loop18      2.7M  2.7M   0 100% /snap/gnome-system-monitor/178
/dev/loop19      2.5M  2.5M   0 100% /snap/gnome-calculator/884
/dev/loop20      56M   56M   0 100% /snap/core18/2566
/dev/loop21      92M   92M   0 100% /snap/gtk-common-themes/1535
/dev/loop22      62M   62M   0 100% /snap/core20/1611
/dev/sda2        96M   52M   45M  55% /boot/efi
tmpfs           3.2G  16K   3.2G   1% /run/user/121
tmpfs           3.2G  0    3.2G   0% /run/user/1000
/dev/nvme0n1p1  226G  28K  215G   1% /media/nvme
hgchoe@ubuntu:~$
```

# Operating Daisy+ OpenSSD (Windows)

- 1. Check device recognition**
- 2. Create a partition**
- 3. Format the partition**

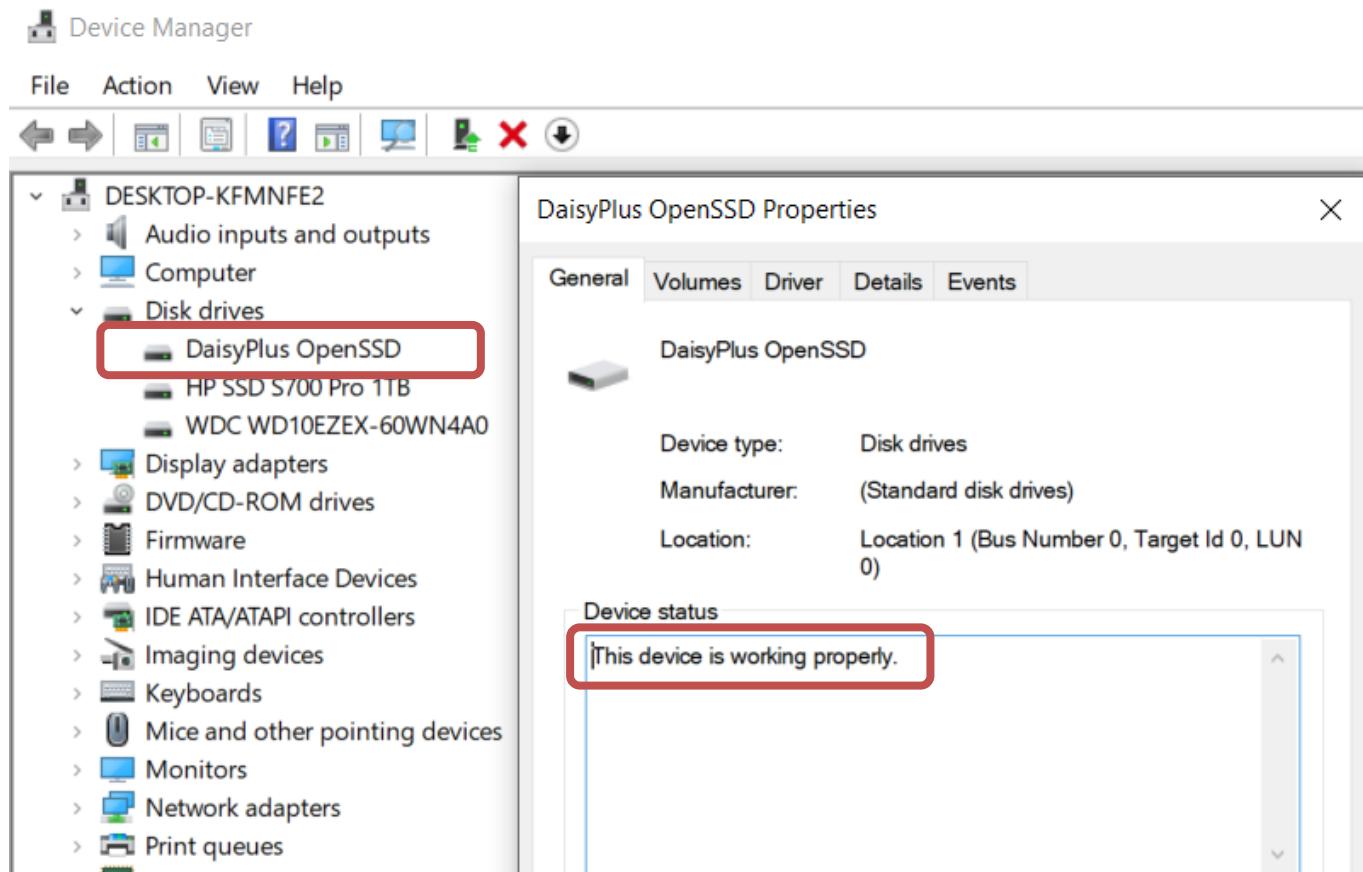
# Check Device Recognition (1 / 2)

- Right-click “Start” menu → click “Device Manager”



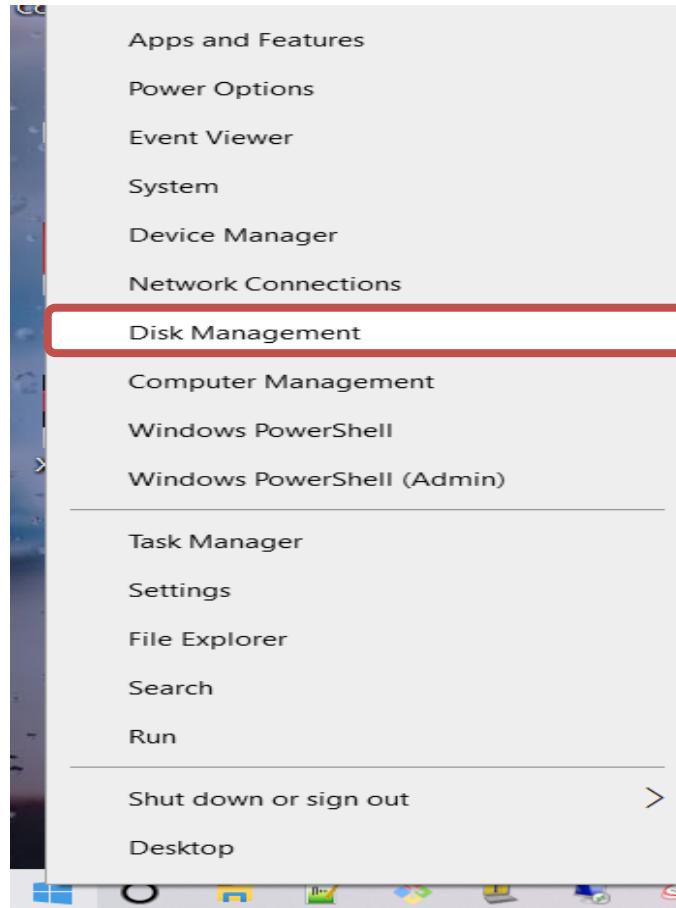
# Check Device Recognition (2 / 2)

- Disk drives → double-click “DaisyPlus OpenSSD”



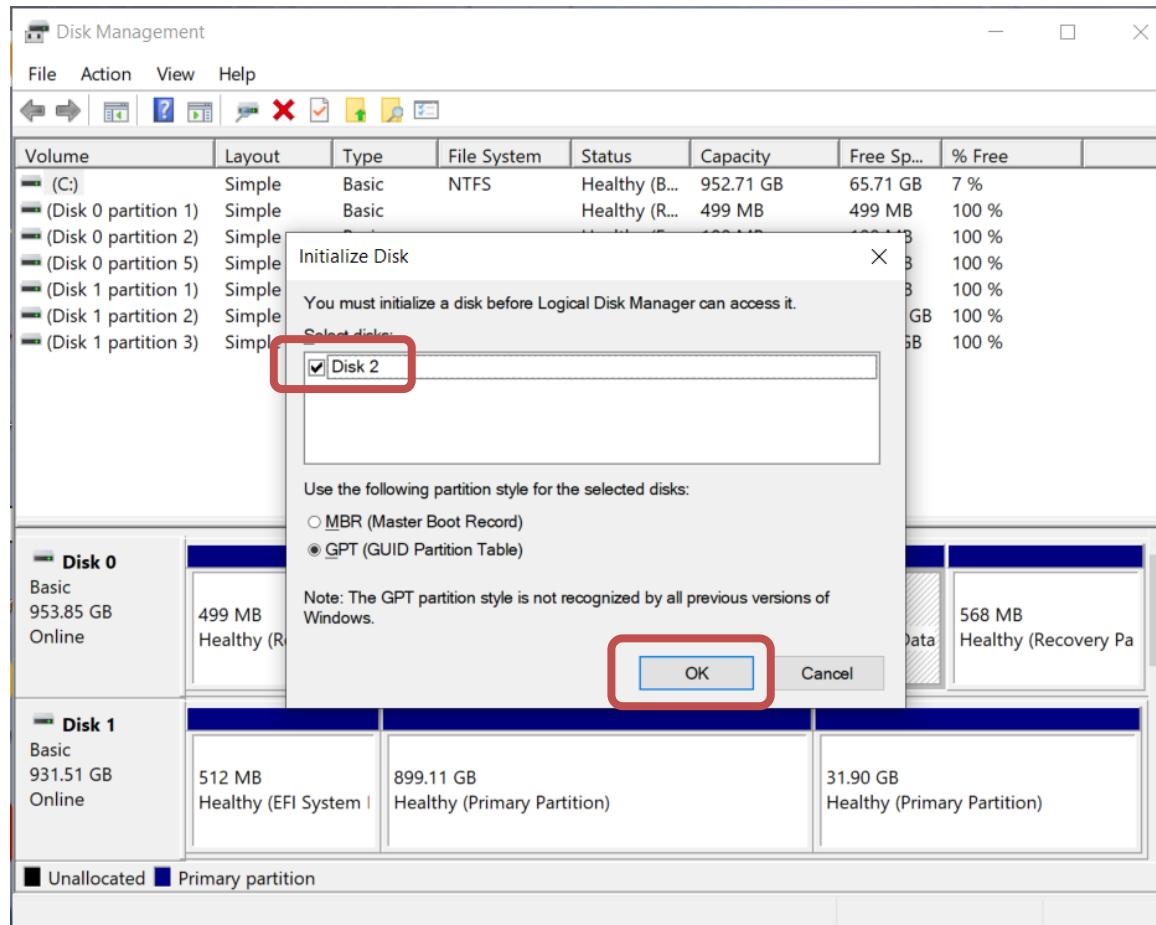
# Create a Partition (1 / 4)

- Right-click “Start” menu → click “Disk Management”



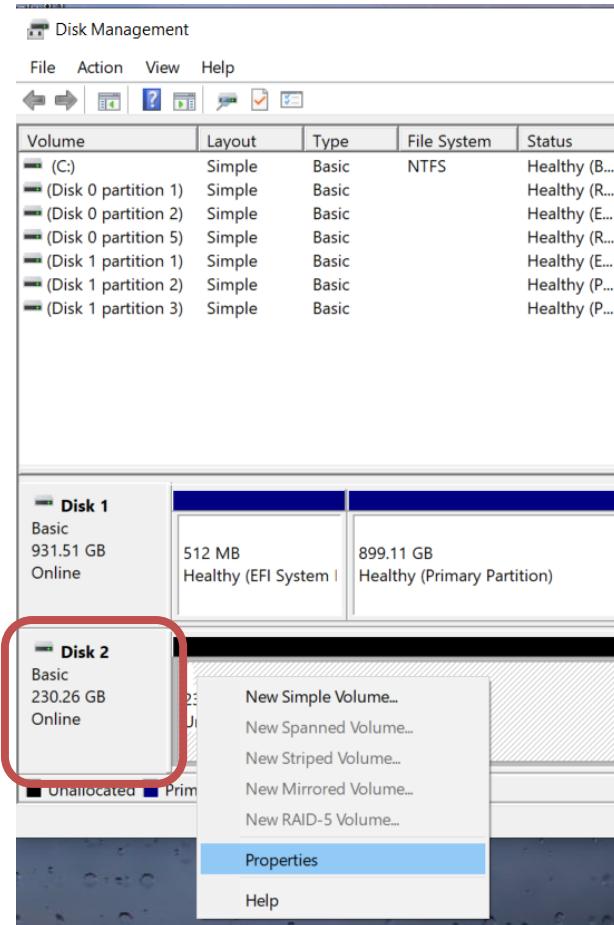
# Create a Partition (2 / 4)

## Click “OK” to confirm disk initialization



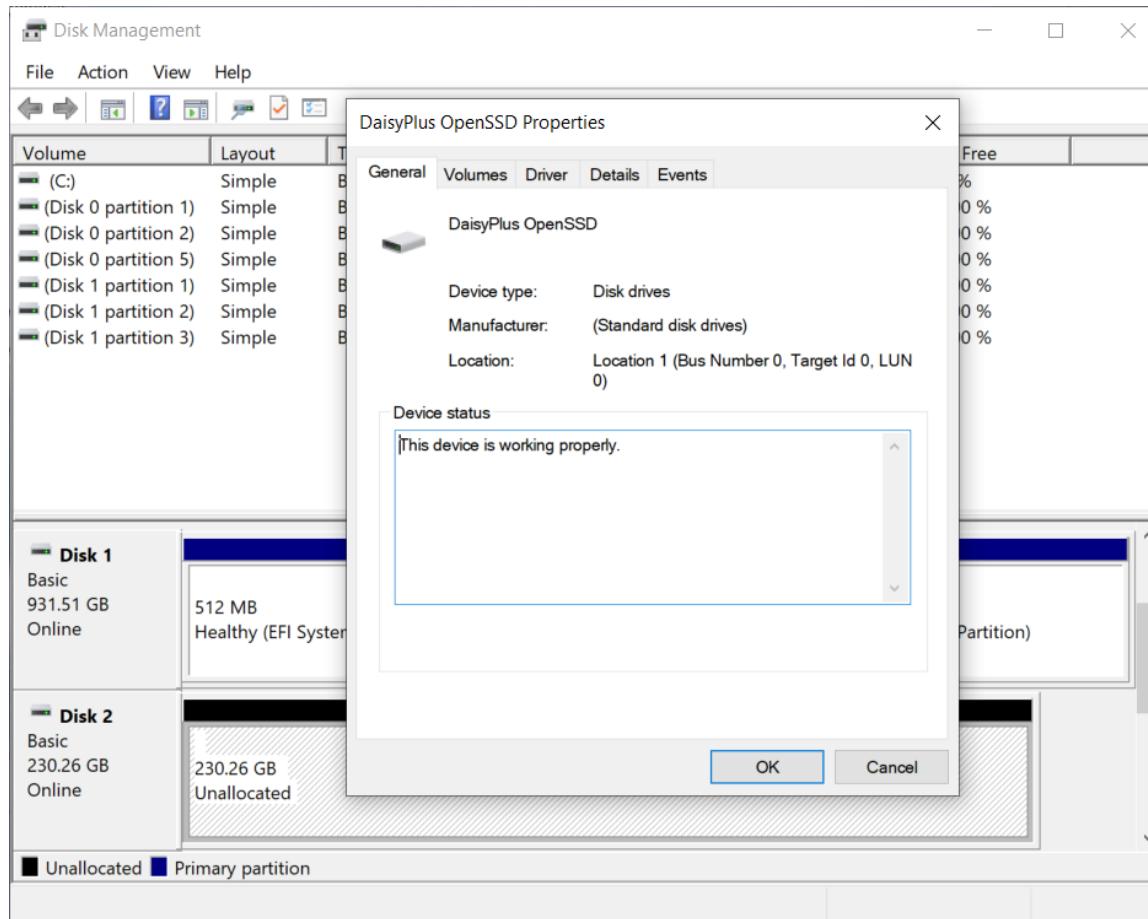
# Create a Partition (3 / 4)

- Click right mouse button on “Disk 2” which was shown in 2<sup>nd</sup> step → click “Properties”



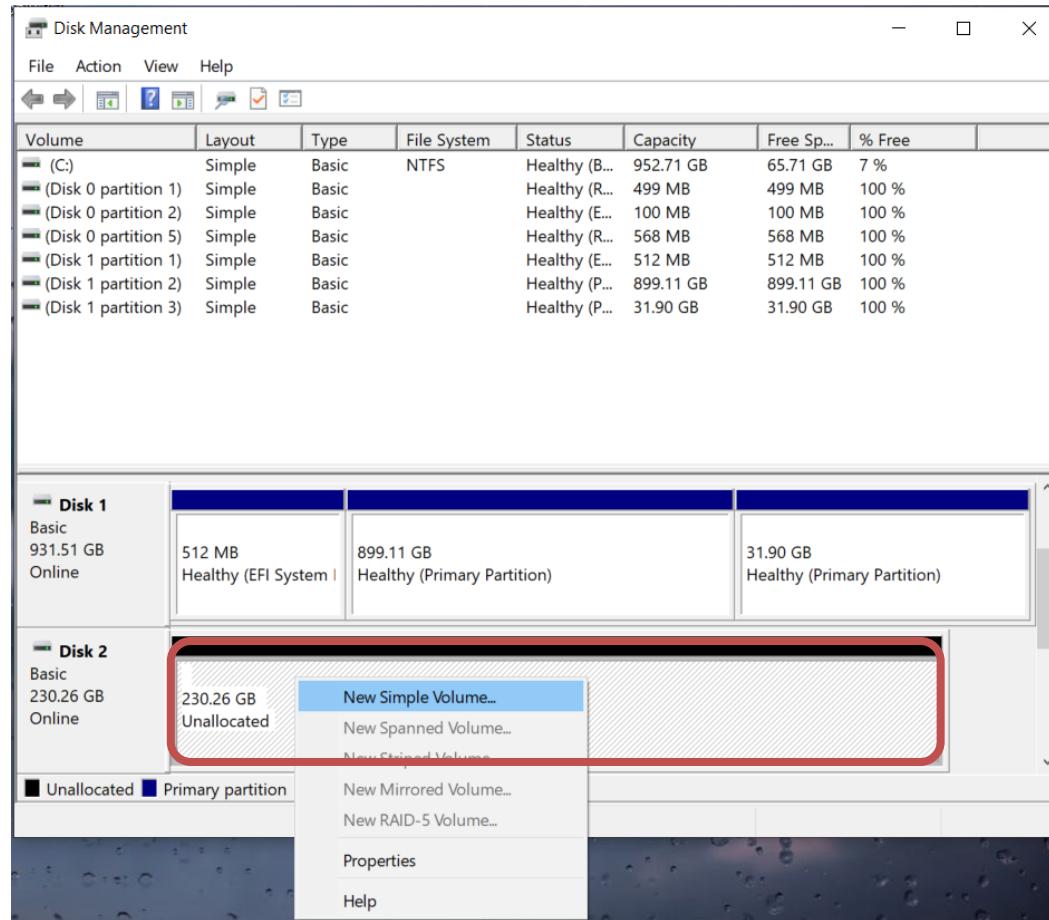
# Create a Partition (4 / 4)

- Make sure that the “Disk 2” is DaisyPlus OpenSSD before you proceed to the next step



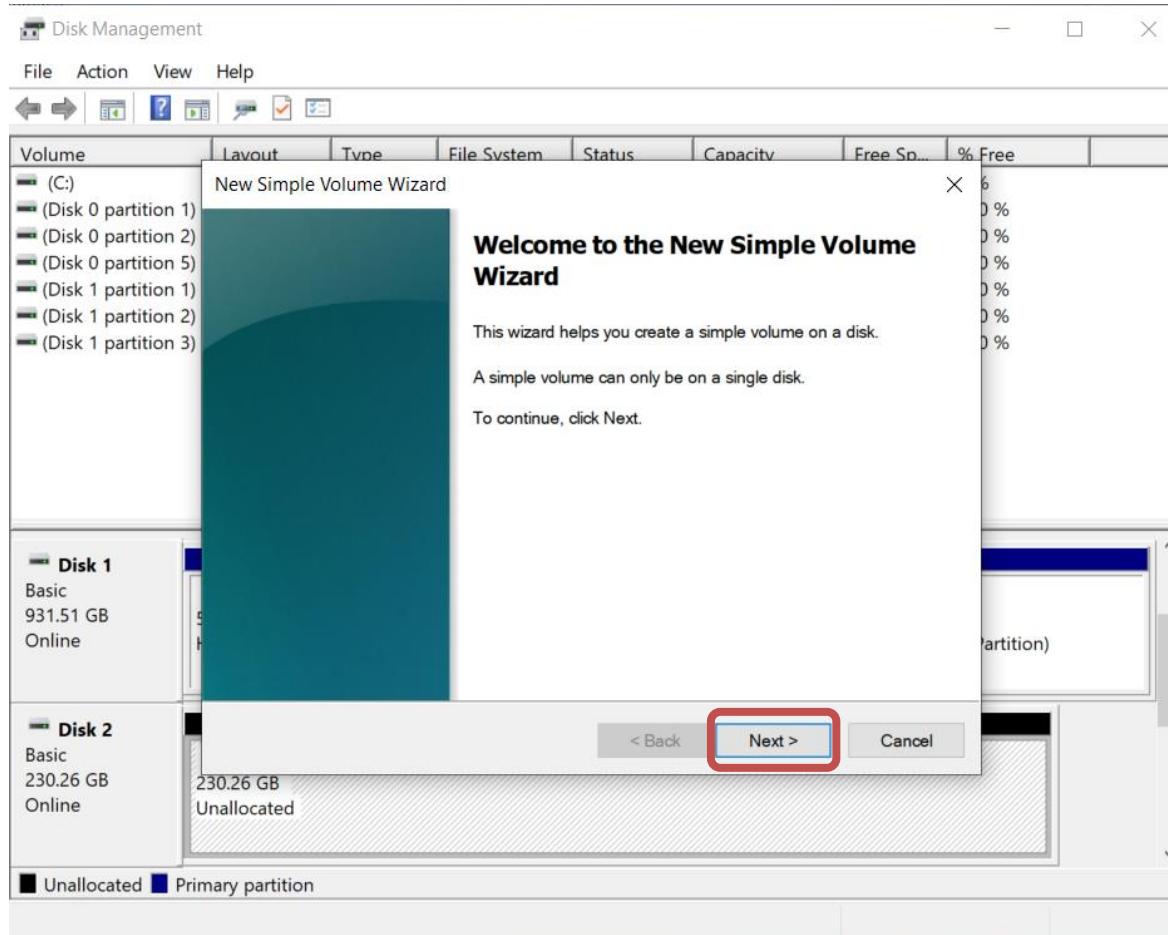
# Format the Partition (1 / 8)

- Click right mouse button on the right part of “Disk 2” → click “New Simple Volume”



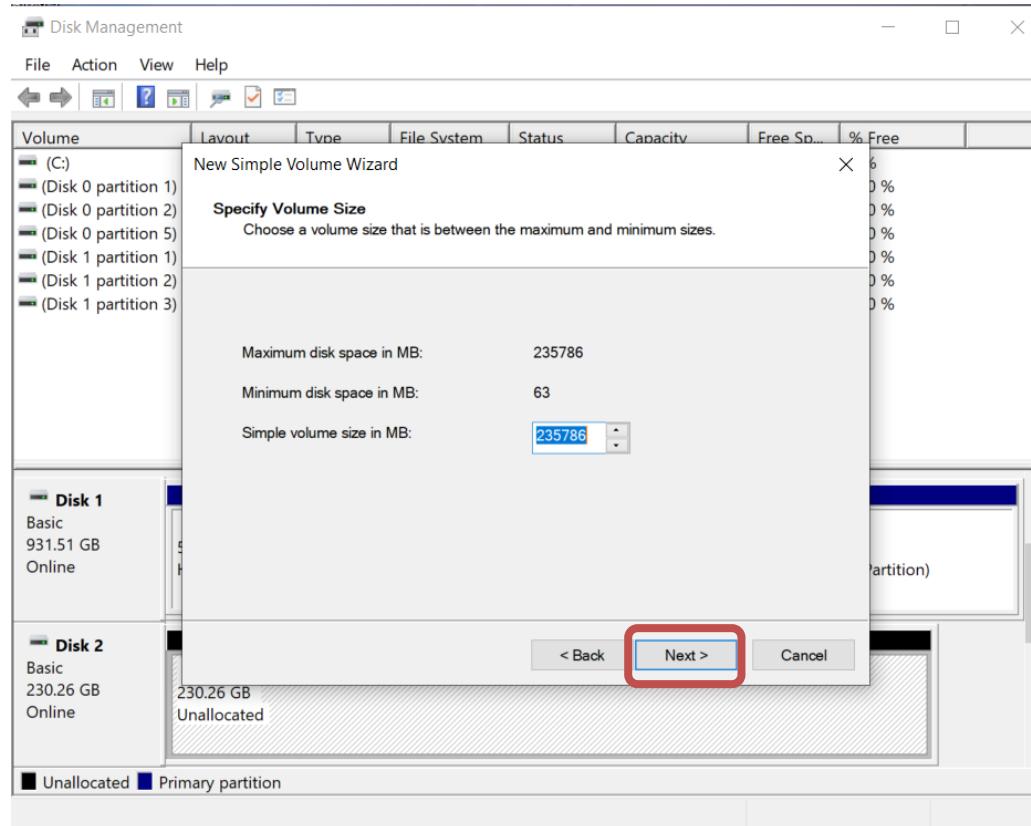
# Format the Partition (2 / 8)

## Click “Next”



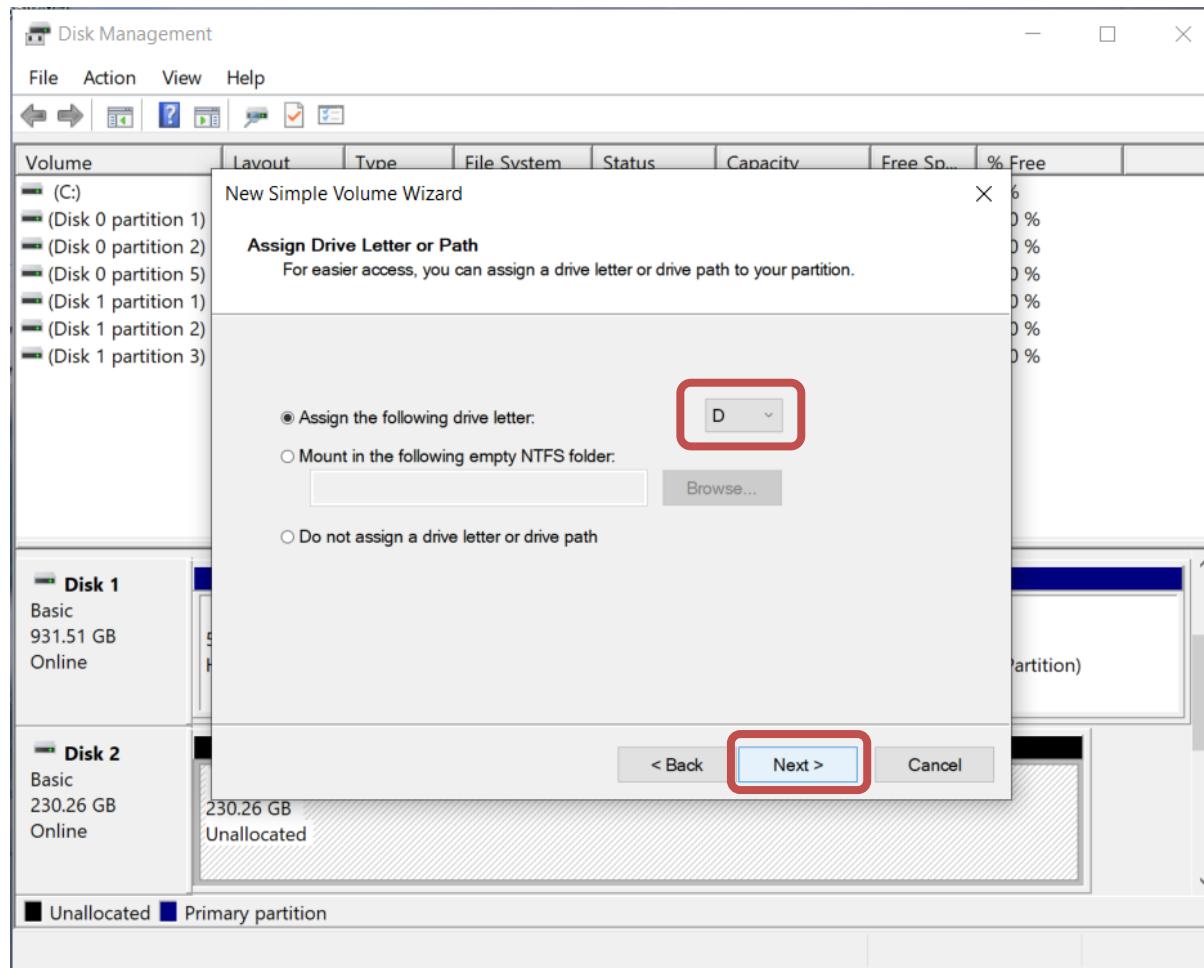
# Format the Partition (3 / 8)

## Click “Next”



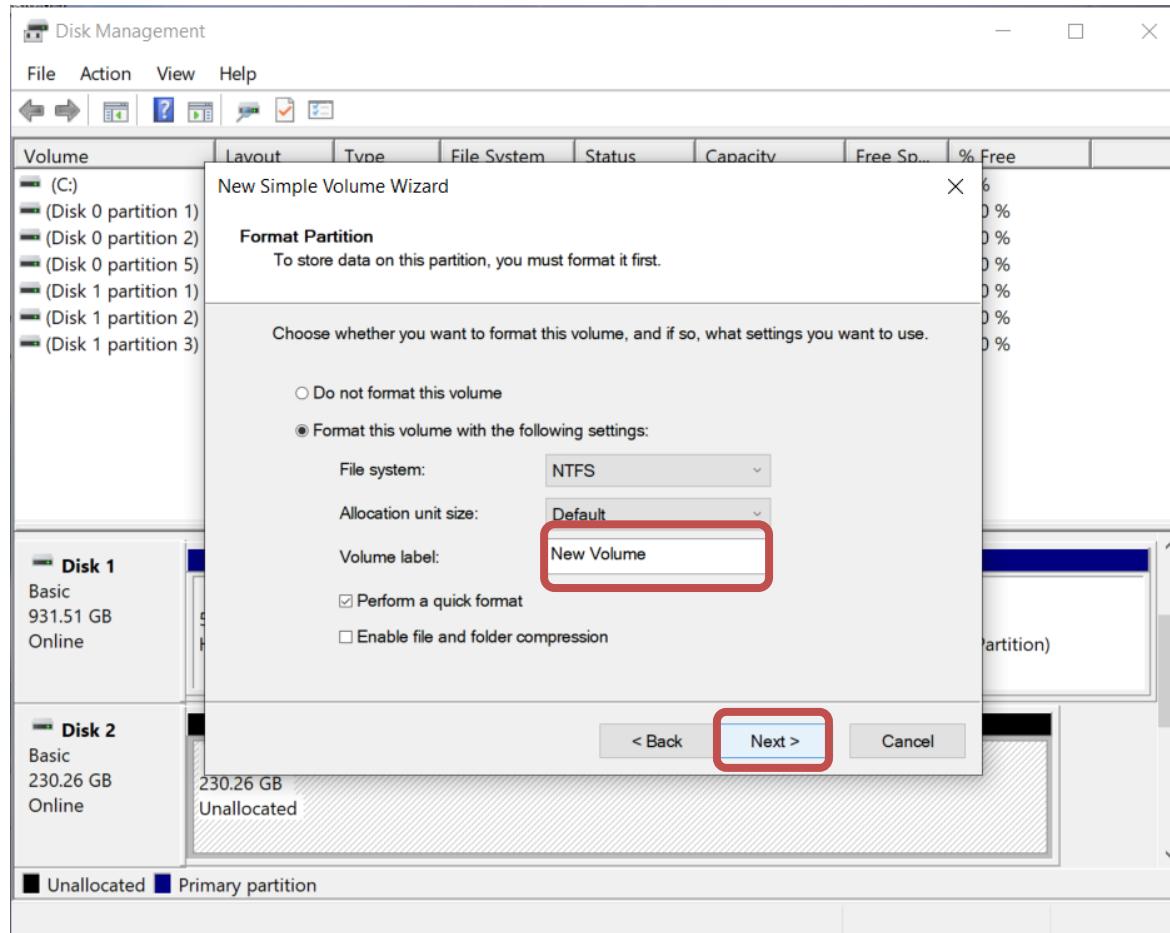
# Format the Partition (4 / 8)

- Select desired drive letter → Click “Next”



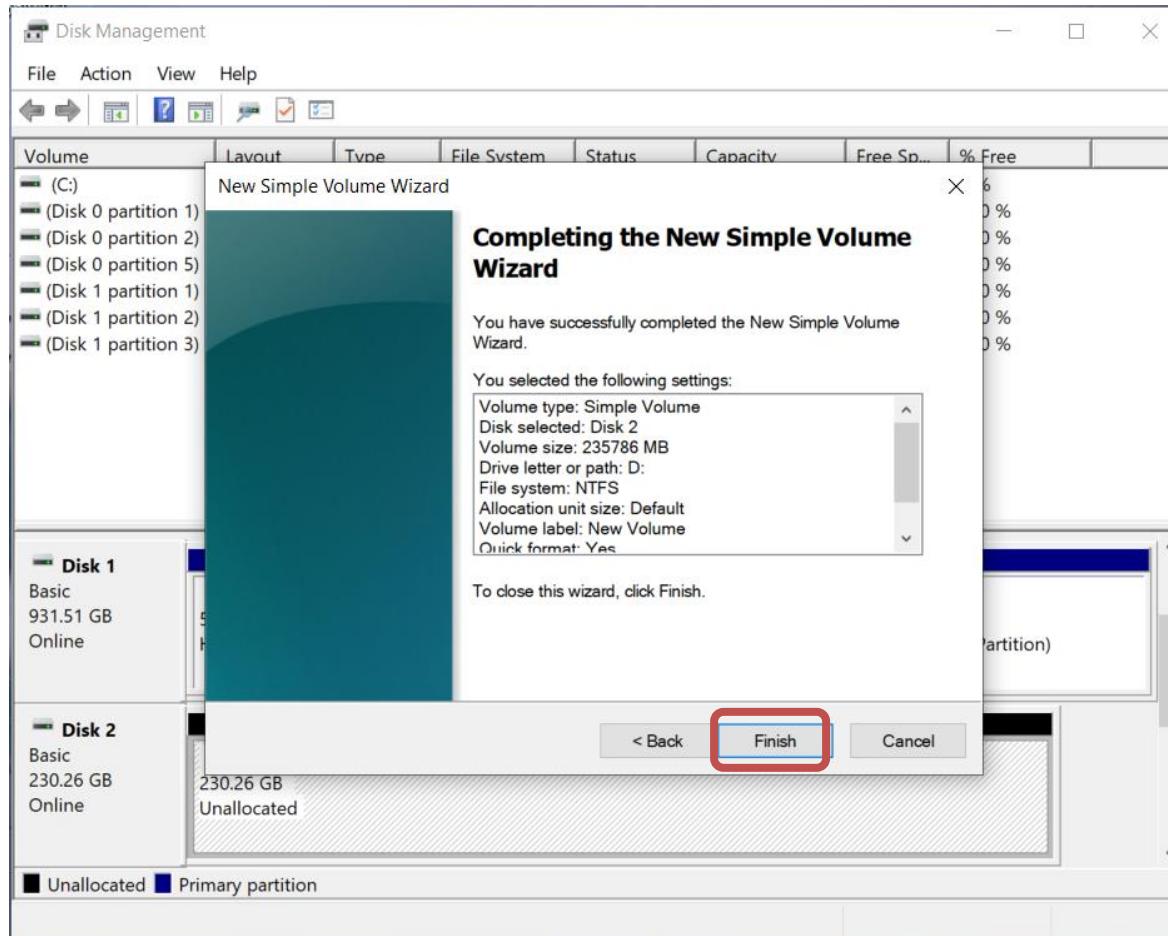
# Format the Partition (5 / 8)

- Type desired volume label → Click “Next”



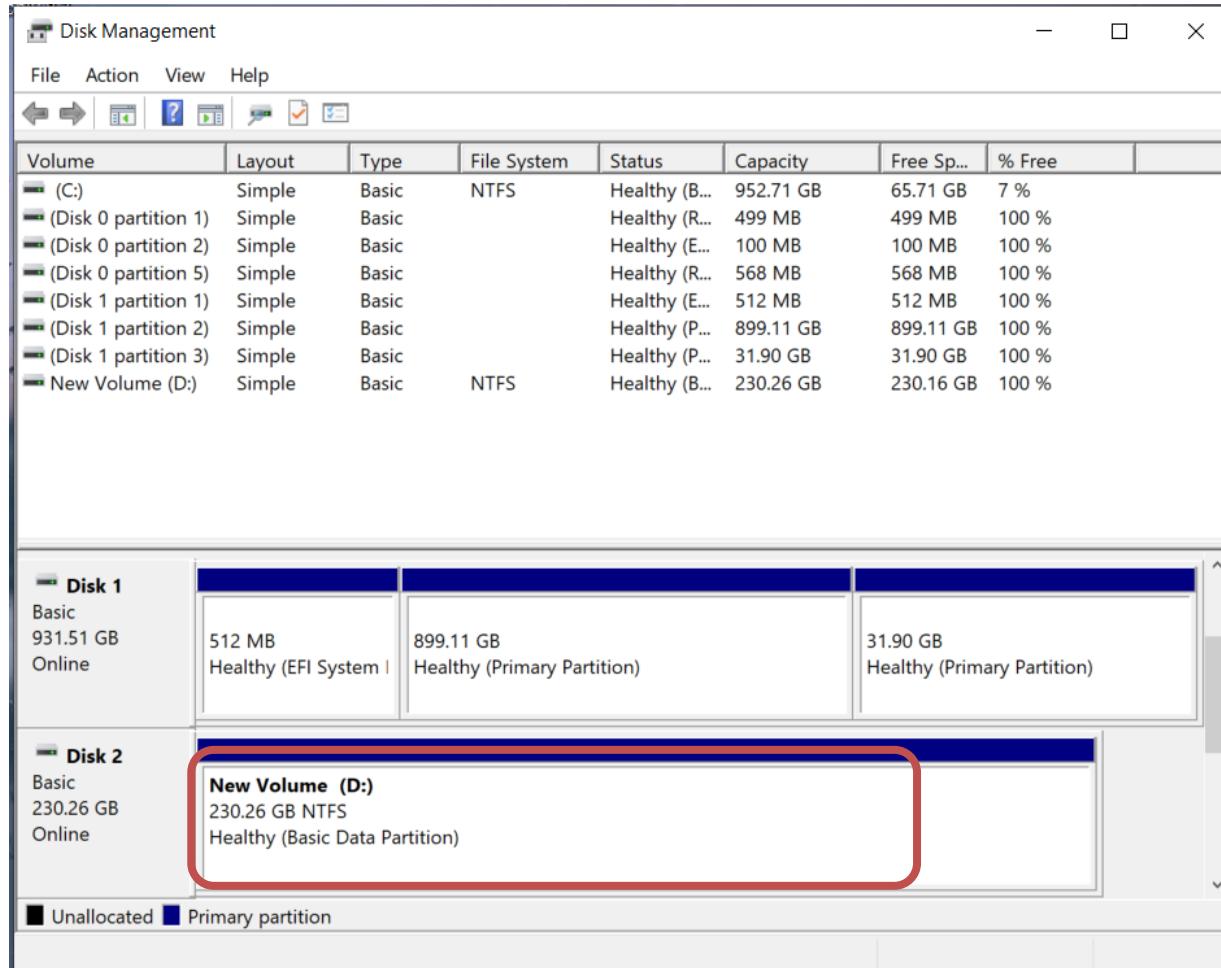
# Format the Partition (6 / 8)

## Click “Finish”



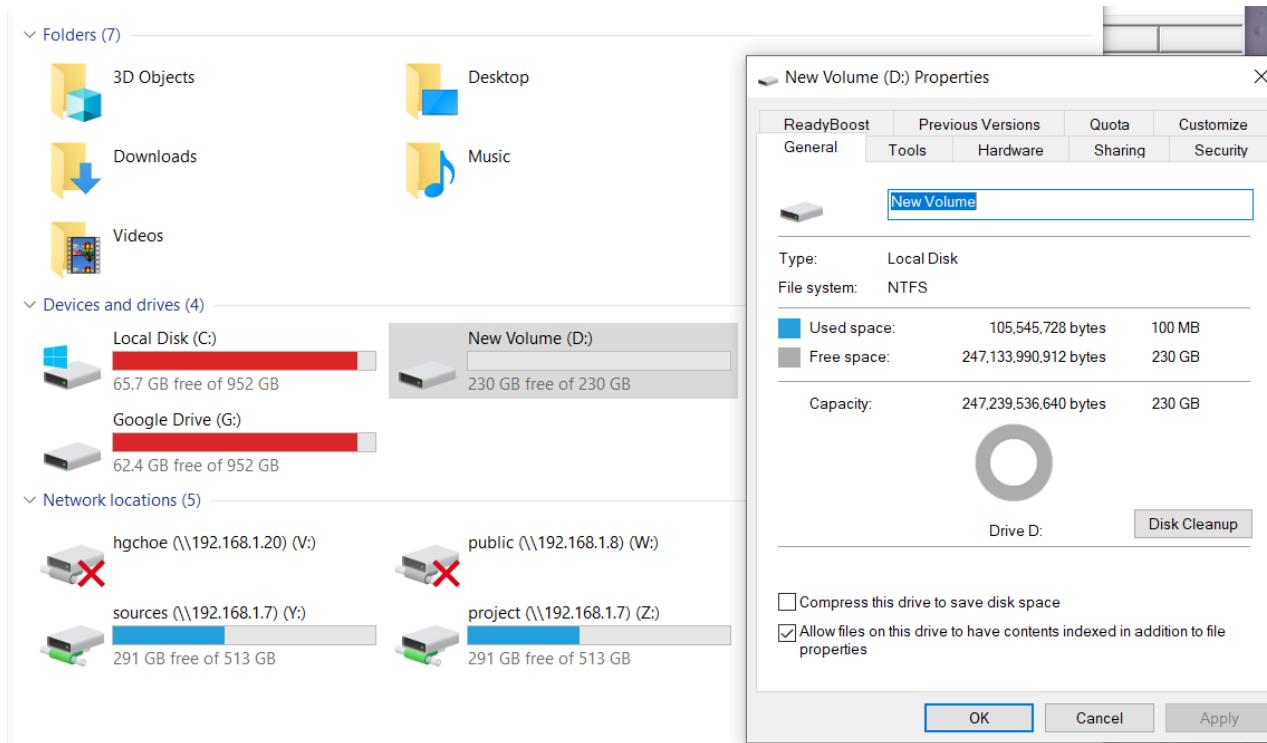
# Format the Partition (7 / 8)

## Formatting is now finished



# Format the Partition (8 / 8)

Now you can find the formatted Daisy+ OpenSSD at “This PC”



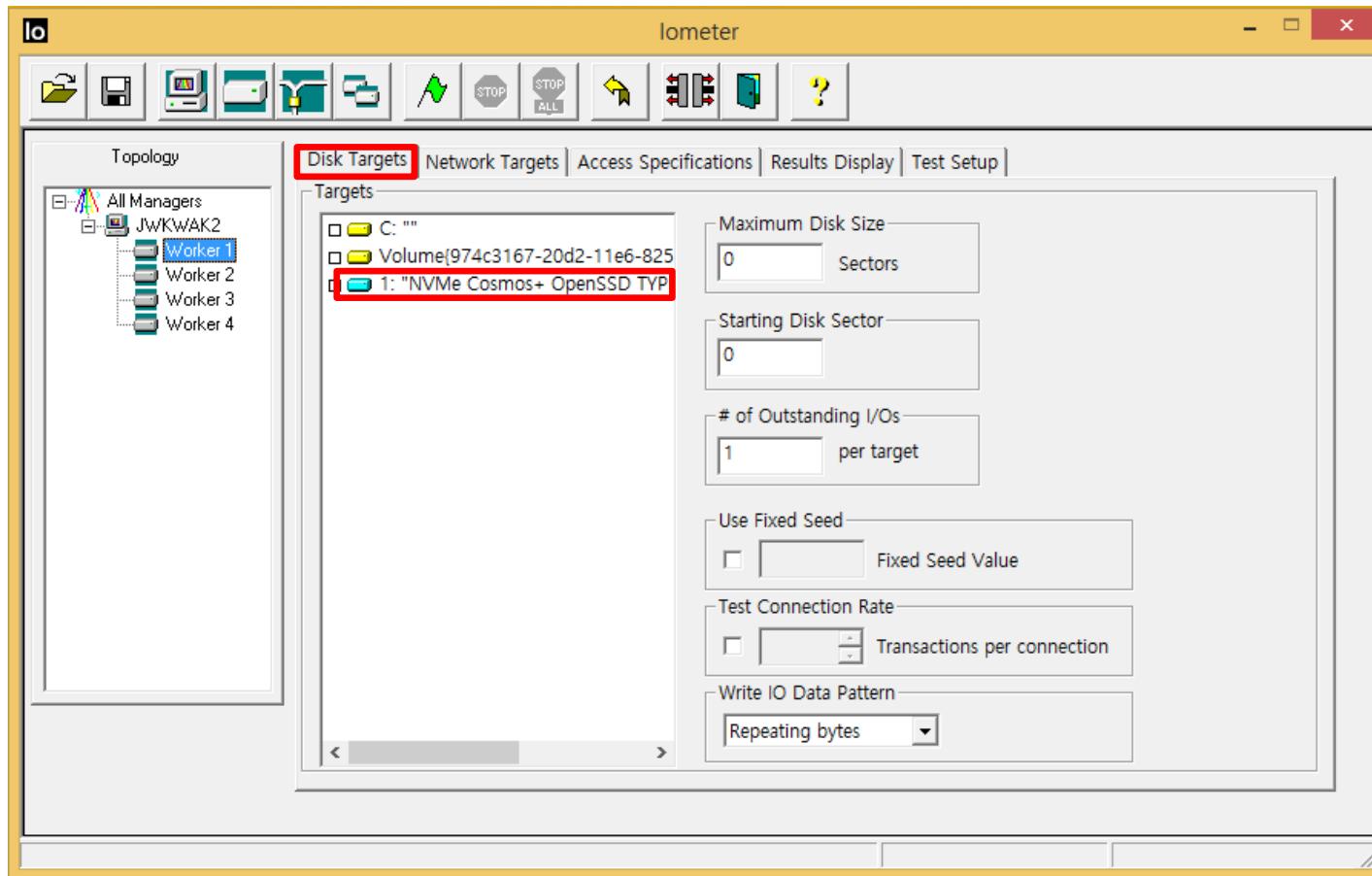
# Evaluating Daisy+ OpenSSD Performance

- 1. Install benchmark application (lometer)**
- 2. Disconnect workers except one worker**
- 3. Generate a access specification**
- 4. Set the sufficient number of outstanding I/Os**
- 5. Assign a access specification**
- 6. Run an evaluation**
- 7. Check evaluation results**

# Install Benchmark Application

## ■ Iometer 1.1.0 (<http://www.iometer.org/doc/downloads.html>)

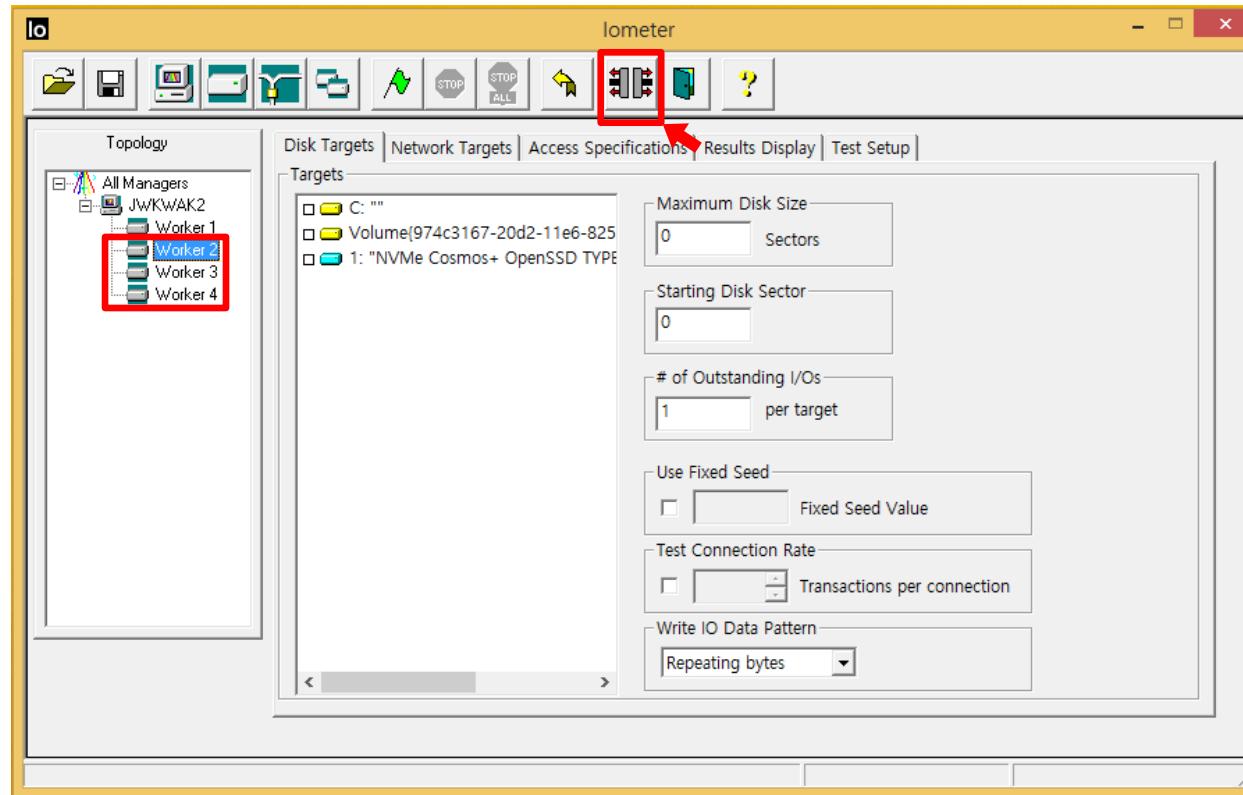
- Cosmos+ OpenSSD is recognized as NVMe storage device



# Disconnect workers except one worker

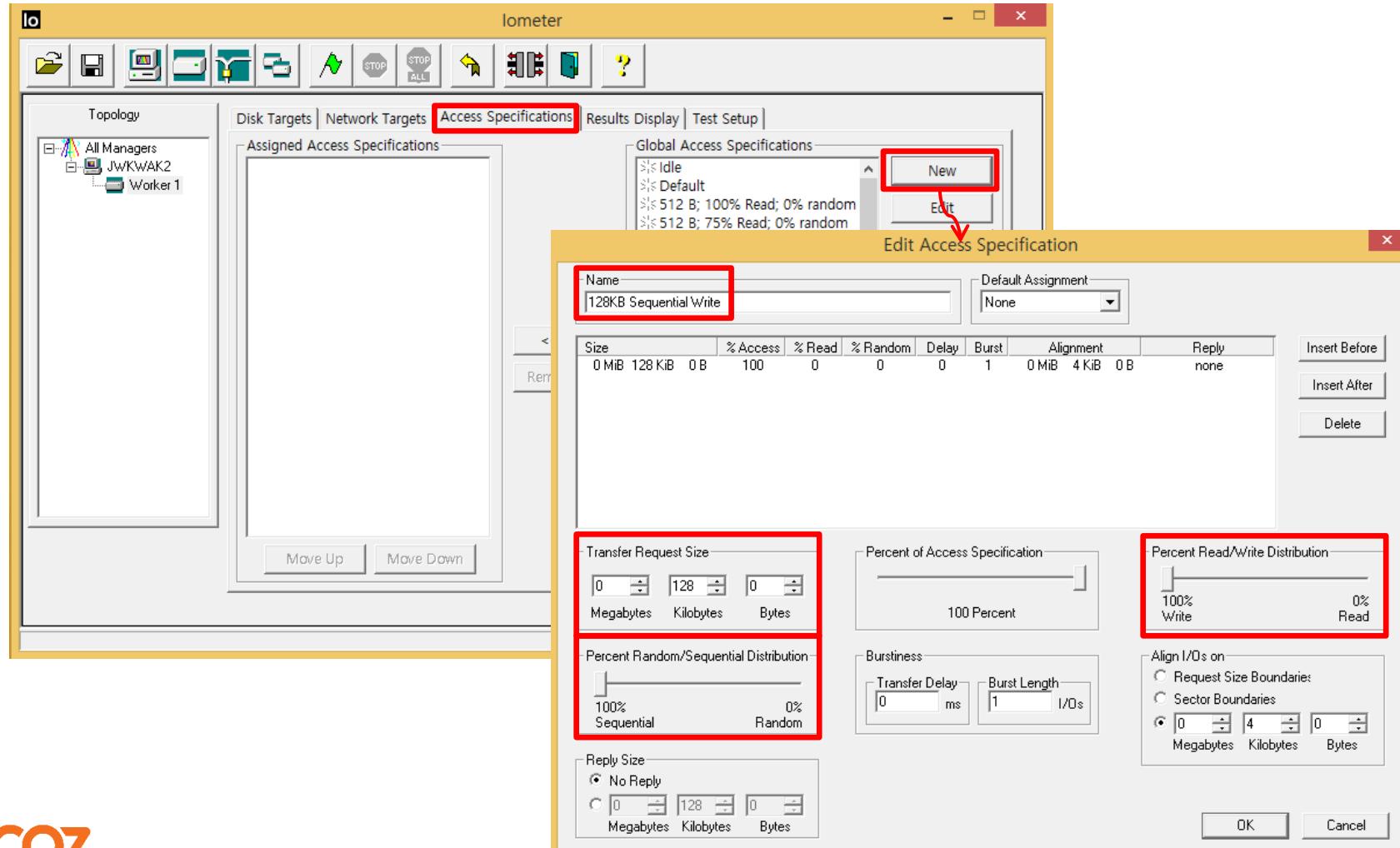
## Avoid Workers having a same access specifications

- Workers can access the same logical address almost the same time
  - Increase the data buffer hit ratio
- Performance can be measured higher than real performance



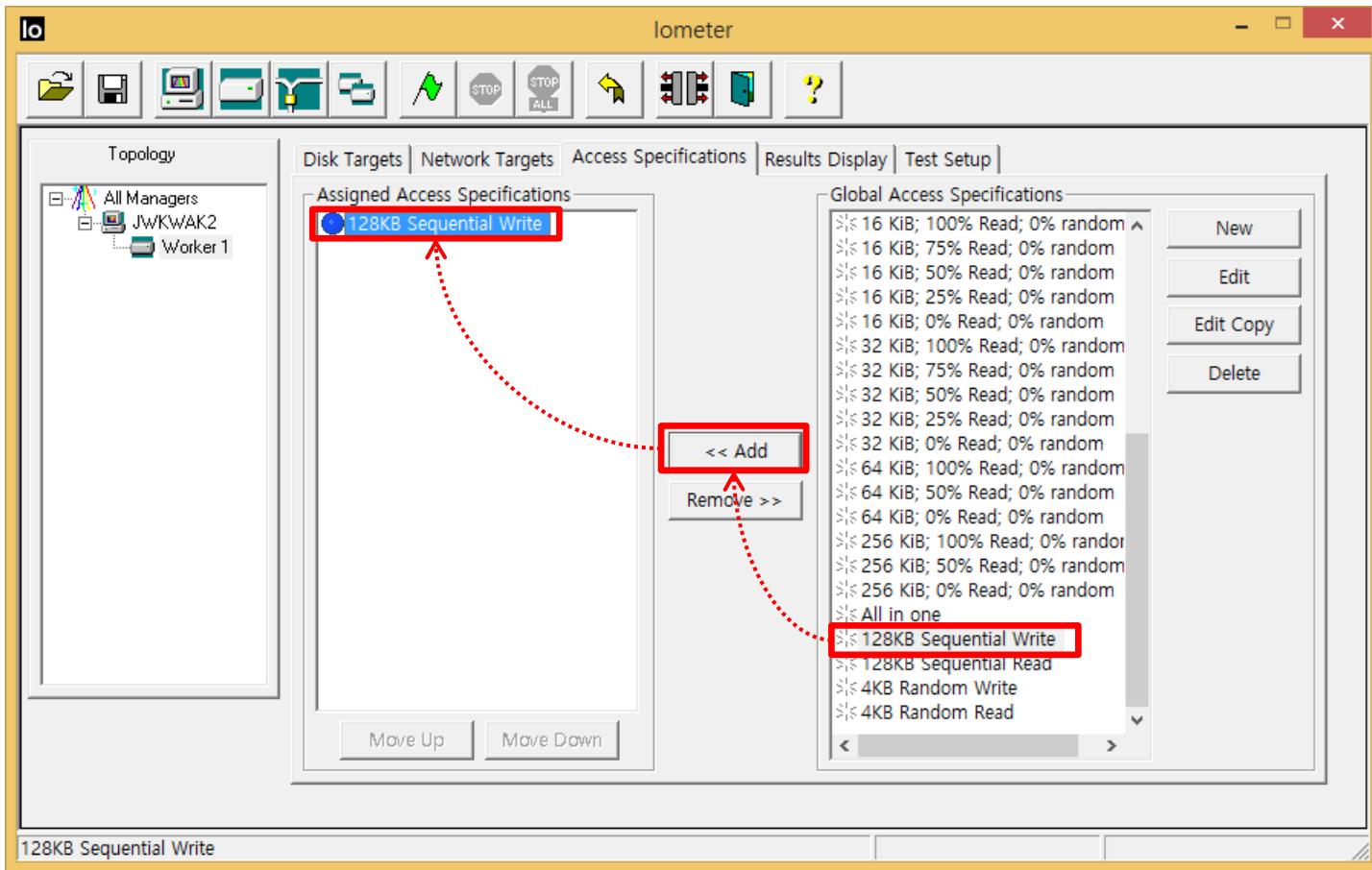
# Generate a access specification

## User can define a access specification



# Assign a access specification

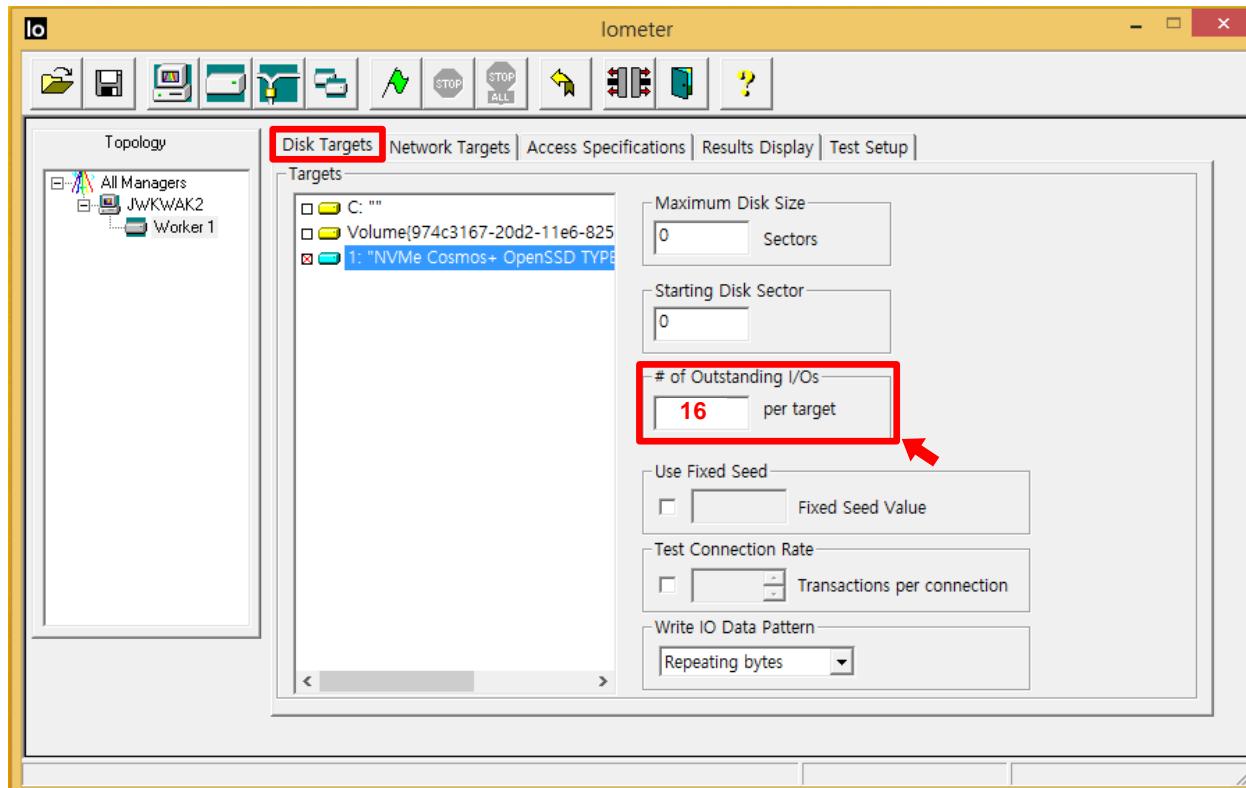
- Select a desired access specification and click “Add” button



# Set the Sufficient Number of Outstanding I/Os

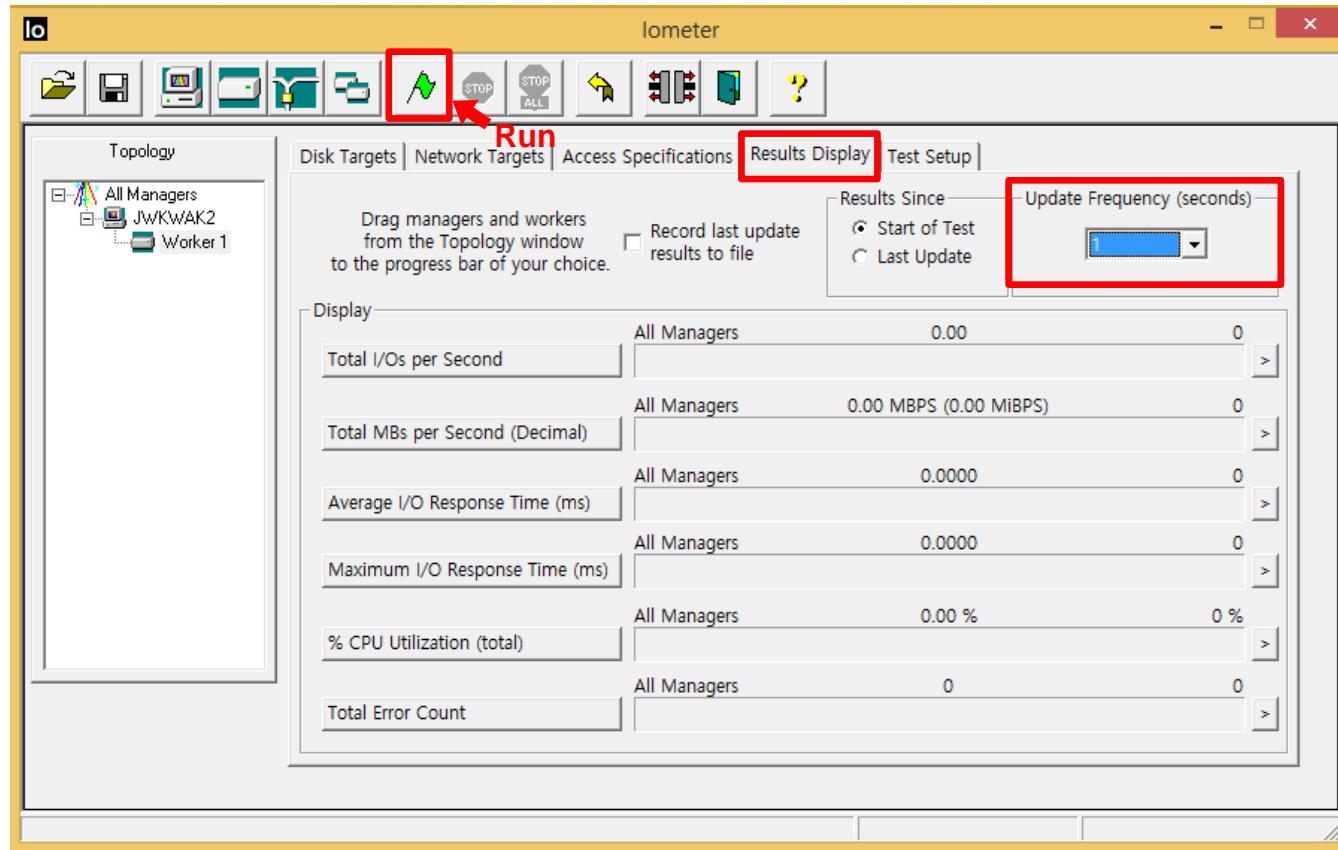
- X channel – Y way flash array needs “X \* Y” outstanding flash requests at least for utilizing multi channel/way parallelism

- In case of a Cosmos+ OpenSSD configuration (8 channel – 8 way, 16KB page size), “128KB sequential write” access specification needs 8 outstanding I/Os at least  
64 ( $128\text{KB}/16\text{KB} * 8$ ) outstanding flash requests
- Recommend the environment generating  $2 * X * Y$  outstanding flash requests



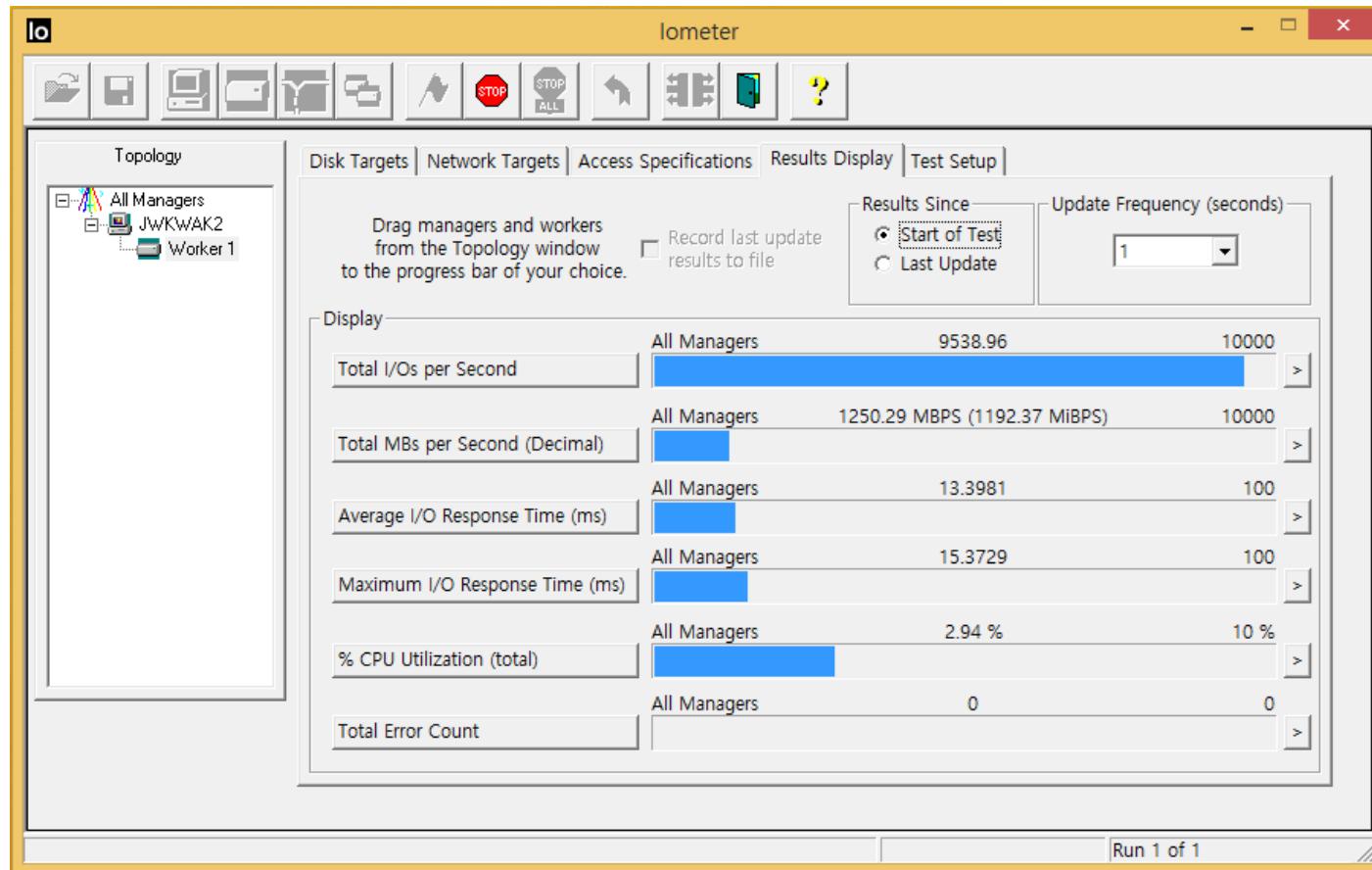
# Run an Evaluation

- Set the update frequency and click “Run” button



# Check evaluation results

- “Results display” tab shows the performance evaluation results
  - IOPs, throughput, average/maximum response time



# Evaluation Guideline

- **Perform pre-fill process before the read performance evaluation**
  - There are no mapping information for unwritten data
- **Set the number of outstanding I/Os equal or less than 256**
  - Unknown problem of host interface
- **Set the write request size equal or larger than the page size**
  - Read-modify-write process can degrade the performance
    - In case of “4KB random write”, IOPs can be decreased as the experiment progresses

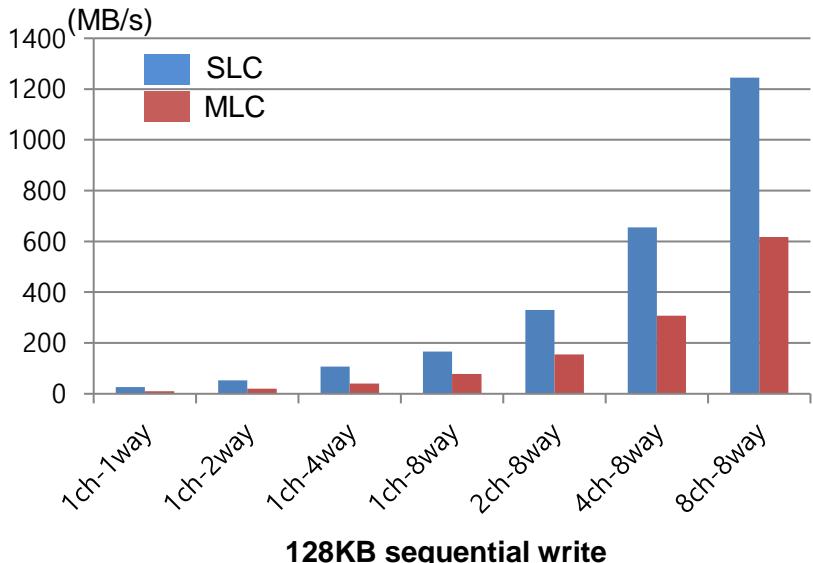
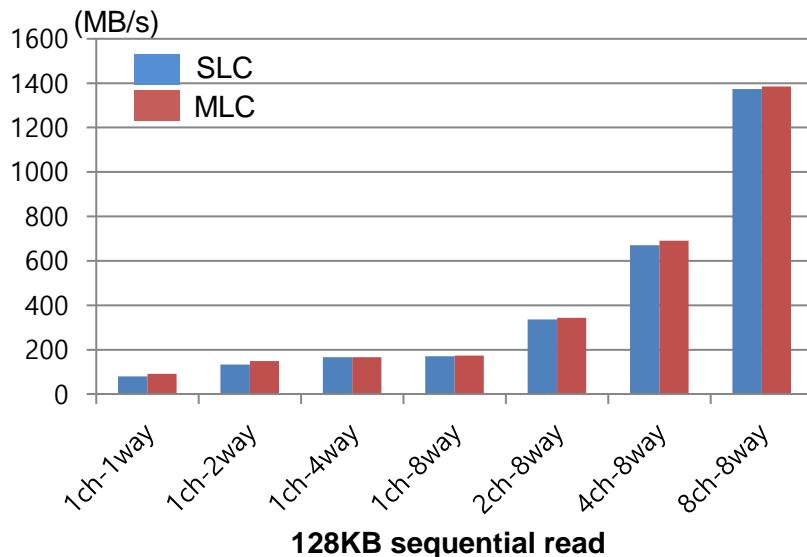
# Evaluation Results (1 / 3)

## ■ Maximum throughput/channel ≈ 173 MB/s

- 100Mhz DDR flash bus (bit width: 8) → 200MB/s
- $16,384 + 1,664(\text{spare})$  byte page → 90% ( $16,384/18048$ ) of 200MB/s = 181MB/s
- Overhead of flash memory controller → 173 MB/s

## ■ Measured throughput/channel of 8channel-8way configuration

- Sequential read: 99% of maximum throughput
- Sequential write: 45~90% of maximum throughput



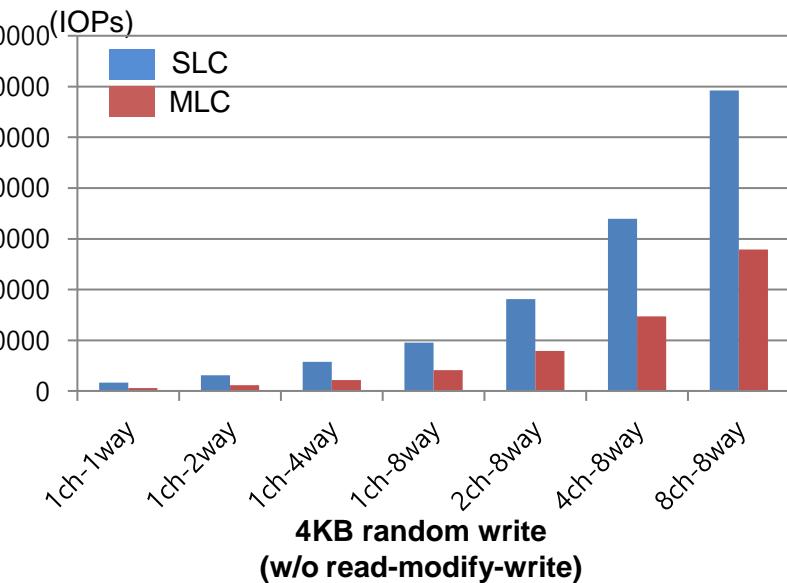
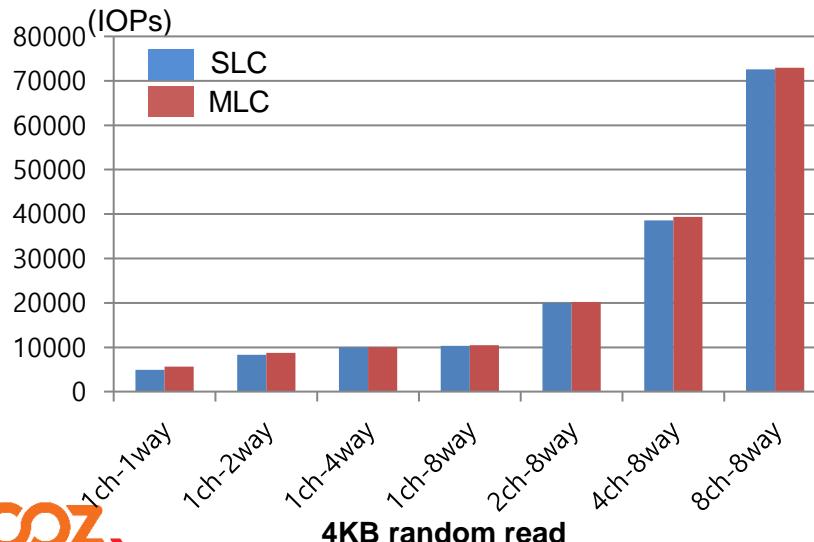
# Evaluation Results (2 / 3)

## ■ Maximum 4KB IOPs/channel ≈ 10812 IOPs

- Page mapping → a page is accessed in order to access 4KB data
- $173\text{MB/s}(\text{Maximum throughput/channel}) \div 16\text{KB} (\text{page size}) = 10812 \text{ IOPs}$

## ■ Measured throughput/channel

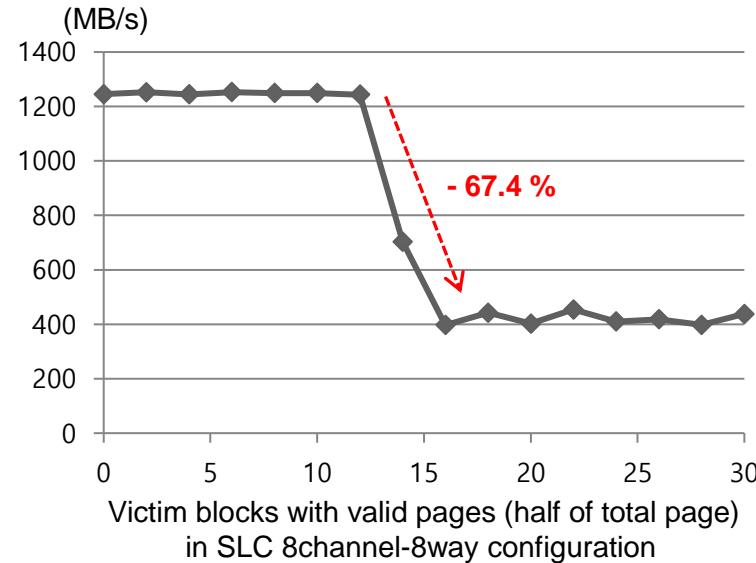
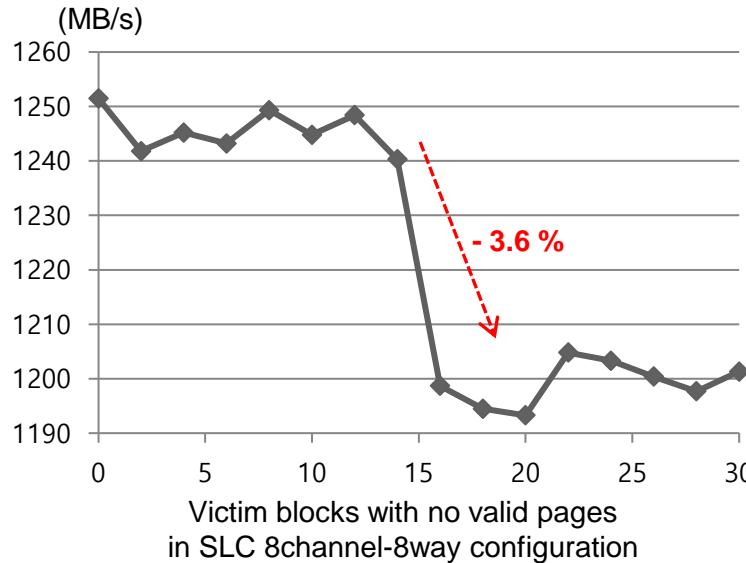
- 1channel-8way configuration
  - Random 4KB read: 96% of maximum 4KB IOPs
  - Random 4KB write: 38~88% of maximum 4KB IOPs
- 8channel-8way configuration
  - SW-based scheduling has a larger latency in many channel/way configuration
  - Scheduling latency can increase the idle time of hardware controllers



# Evaluation Results (3 / 3)

## Performance degradation by on-demand garbage collection

- After all available blocks are used, garbage collection is triggered steadily
- Effect of performance degradation varies depending on copy operation overhead
  - Copy operation overhead depends on the number of valid page belong to victim blocks



# Thank You

