

Accelerating Verification of Computational Storage Designs

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Agenda

❑ The Next Era of storage technology

- Computational Storage
- Traditional vs Computational storage model
- What's New

❑ Functional Verification

- Challenges
- Solution



The Next Era of Storage Technology

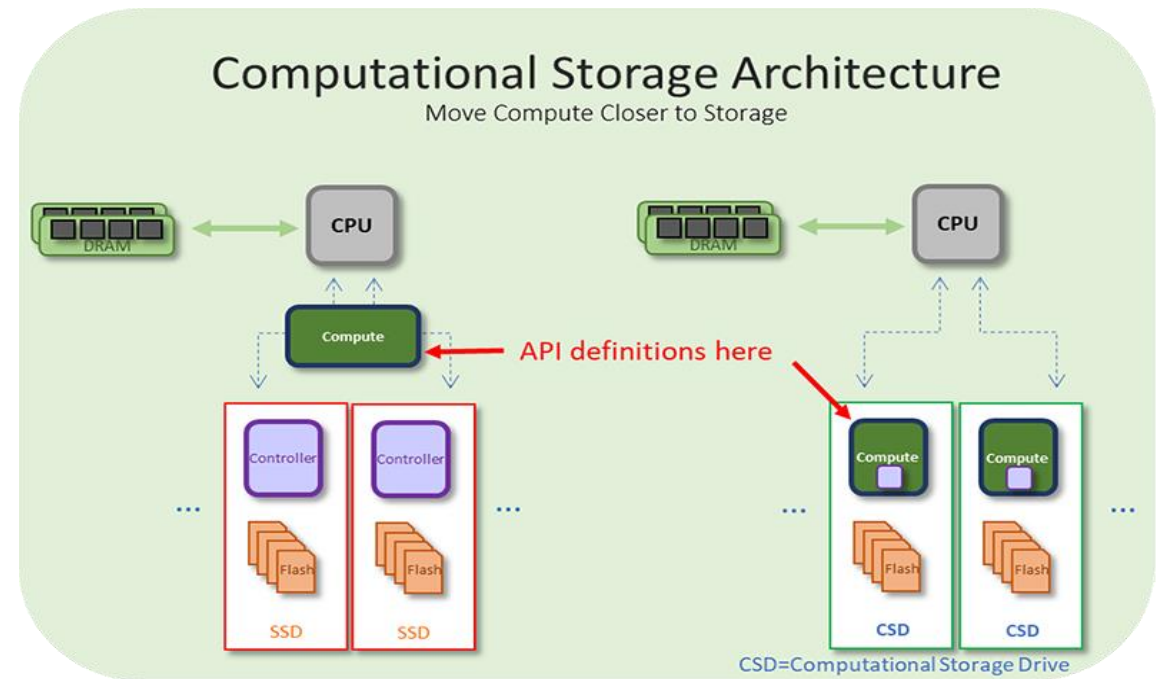
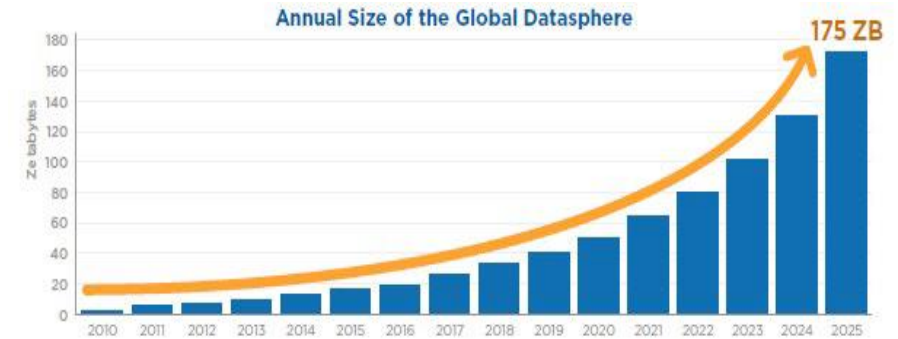


Computational Storage

- Exponential growth in data
- Need for faster, efficient data processing solution

□ Solution

- Replacing traditional NVMe SSDs with Computational Storage drive (CSDs)
- Integrates processing power directly into the storage device



Traditional vs Computational Storage Model



Benefits of Computational Storage

- Offloading host processing
- Reduces data movement
- Improved Performance
- Lower latency
- Bandwidth efficiency



What's New

□ Command Sets

- Computational Program
- Subsystem Local Memory

□ Namespaces

- Compute - resource on which program are stored and executed
- Memory - resource on which I/O data for programs is stored



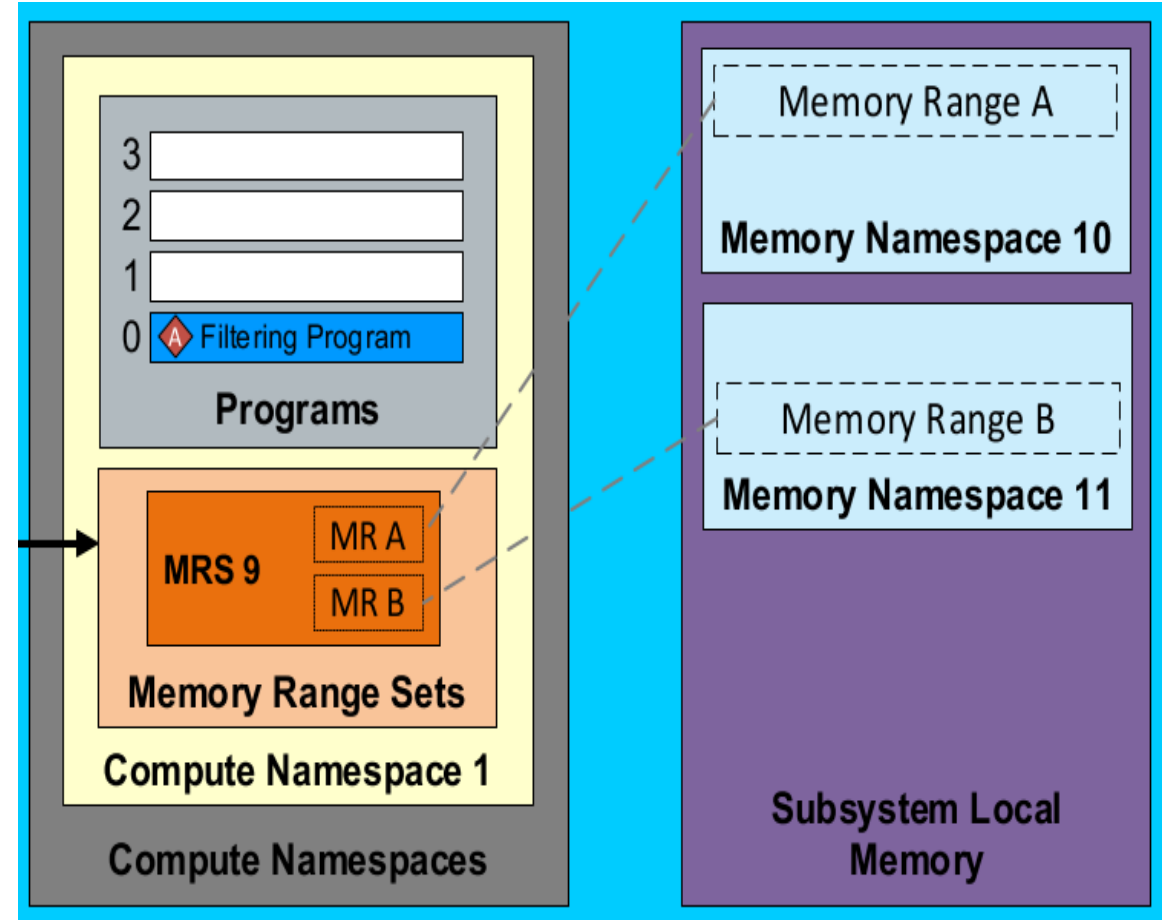
What's New

□ Programs

- Functional pieces of code designed to accomplish a well-defined purpose
 1. Downloadable
 2. Device-defined

□ Memory Range Sets

- Collection of memory namespace ranges
- Specific to a compute namespace



Functional Verification

Challenges & Solution



Protocol Compliance

➤ verifying that Computational Programs and SLM commands do not introduce protocol violations or unexpected behaviour

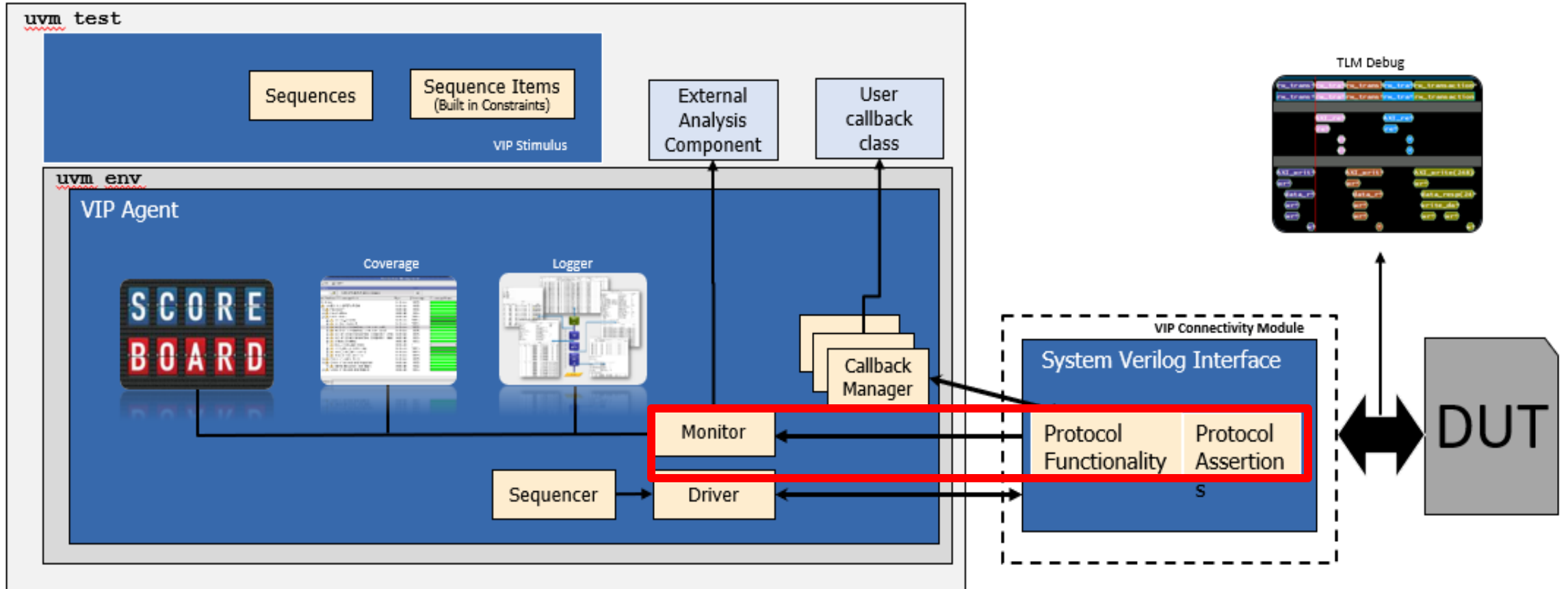
☐ Independent Monitor

- Decodes all transport packets
- Watches complete address space
- Checks for any unnecessary/ unrelated transport packets
- Can be plugged into existing test environment



Protocol Compliance

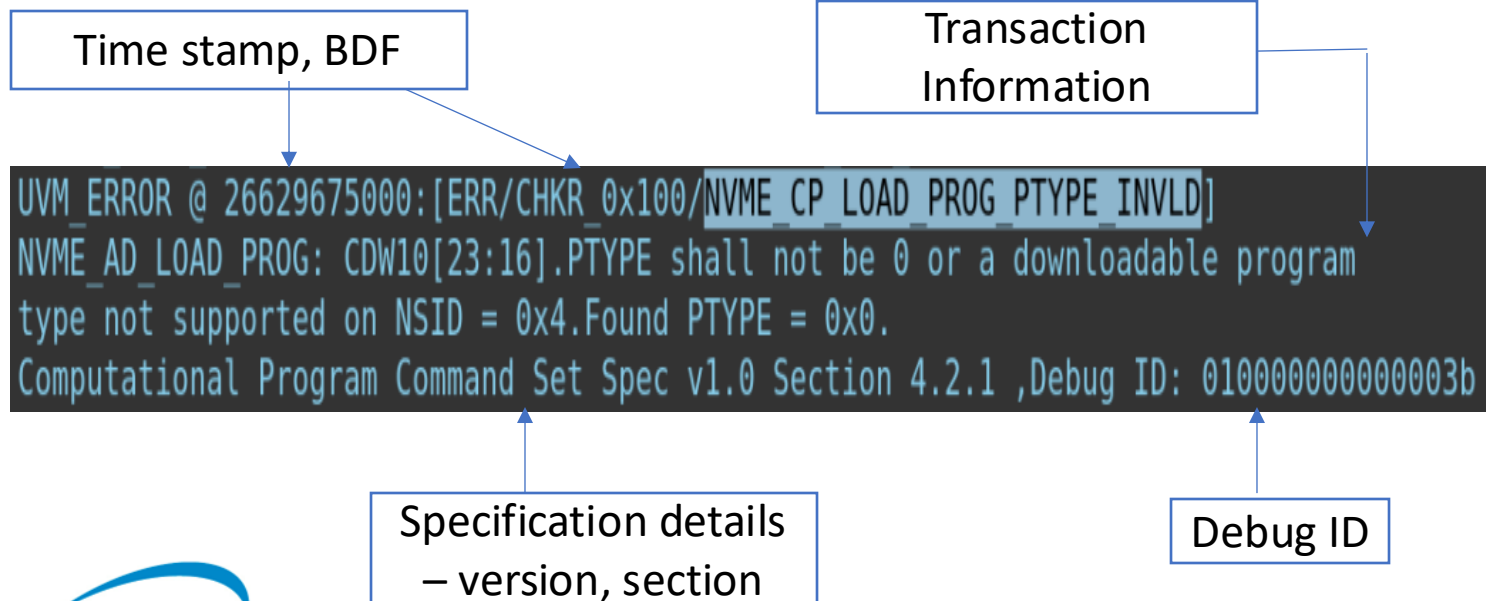
Independent Monitor



Protocol Compliance

Exhaustive Protocol suite

- Around 1100+ protocol checks
- Around 100+ assertions based on Computational Program and SLM command set



```
// CP Checks
NVME_CP_NSDS_RSVD,
NVME_CP_CDS_RSVD,
NVME_CP_CDS_VER_INVLD,
NVME_CP_PIND_INVLD,
NVME_CP_LOAD_PROG_PIT_RSVD,
NVME_CP_LOAD_PROG_PTYPE_RSVD,
NVME_CP_LOAD_PROG_PTYPE_INVLD,
NVME_CP_LOAD_PROG_PSIZE_EXCEED,
NVME_CP_LOAD_PROG_NUMB_INVLD,
NVME_CP_LOAD_PROG_LOFF_INVLD,
NVME_CP_SEL_RSVD,
NVME_CP_PROG_ACT_MNG_MAXACT_EXCEED,
NVME_CP_RSID_INVLD,
NVME_CP_MEM_RNG_SET_MNG_NUMR_INVLD,
NVME_CP_MEM_RNG_SET_MNG_MAXMEMRS_EXCEED,
NVME_CP_EXEC_PROG_RSID_NUMR_INVLD,
NVME_CP_EXEC_PROG_DLEN_INVLD,
NVME_CP_MEM_RNG_SET_MNG_MNSID_INVLD,
NVME_CP_MEM_RNG_SET_MNG_MEM_RNG_LEN_INVLD,
NVME_CP_MEM_RNG_SET_MNG_MEM_RNG_OVRLP,
NVME_CP_XPCTD_STS_PIND_NOT_DOWNLDBL,
NVME_CP_XPCTD_STS_INVLD_FLD,
NVME_CP_XPCTD_STS_INVLD_PTYPE,
NVME_CP_XPCTD_STS_INVLD_PIND,
NVME_CP_XPCTD_STS_MAXPB_EXCEED,
NVME_CP_XPCTD_STS_NO_PROG,
NVME_CP_XPCTD_STS_MAXACT_EXCEED,
NVME_CP_XPCTD_STS_INVLD_RSID,
NVME_CP_XPCTD_STS_MAXMEMR_EXCEED,
NVME_CP_XPCTD_STS_MAXMEMRS_EXCEED,
NVME_CP_XPCTD_STS_PROG_NOT_ACT,
NVME_CP_XPCTD_STS_INVLD_MEM_NS,
NVME_CP_XPCTD_STS_INVLD_MEM_RNG_SET,
NVME_CP_XPCTD_STS_OVRLP_MEM_RNG,
NVME_GETLP_PTYPE_INVLD,
NVME_GETLP_PTYPE_RSVD,
NVME_DPROG_LIST_LP_DESC_VER_INVLD,
NVME_DPROG_LIST_LP_DESC_RSVD,
NVME_PROG_LIST_LP_PEOCC_RSVD,
NVME_PROG_LIST_LP_PIT_RSVD,
NVME_PROG_LIST_LP_PIT_INVLD,
NVME_PROG_LIST_LP_PID_INVLD,
NVME_PROG_LIST_LP_DESC_RSVD,
NVME_MEMRS_LIST_LP_MAXMEMRS_EXCEED,
NVME_MEMRS_LIST_LP_RSID_INVLD,
NVME_MEMRS_LIST_LP_MAXMEMR_EXCEED,
NVME_MEMRS_LIST_LP_MNSID_INVLD,
NVME_MEMRS_LIST_LP_MEM_RNG_LEN_INVLD,
NVME_MEMRS_LIST_LP_OVRLP_MEM_RNG,
```



Stimuli / Testing

- directed testing – creating exhaustive test plans
- stress testing – assessing system behaviour under high-load conditions
- validating error detection and reporting across the computational storage, subsystem local memory
- Handling concurrent operations between computational tasks and standard NVMe operations



Stimuli / Testing

❑ Transport Independent Stimulus Library

- Around 800+ built-in sequences

❑ Highly configurable command structure

❑ Wide pool APIs to set/get command field

❑ Randomization of Stimulus

- corner cases and unexpected scenarios

❑ Automating command creation

- Constraints, APIs
- minimized user input for stress-testing

❑ Error Injection

- Built-in error scenario sequences, Error structure ,Callbacks

```
▼ sequence_lib/  
  ▶ admin_cmd/  
  ▶ base/  
  ▶ boot_partition/  
  ▶ compliance/  
  ▶ cp_cmd/  
  ▶ erroneous/  
  ▶ fabric_cmd/  
  ▶ initialization/  
  ▶ io_cmd/  
  ▶ kv_cmd/  
  ▶ metadata/  
  ▶ namespace/  
  ▶ persistent/  
  ▶ pmr/  
  ▶ prp/  
  ▶ queue/  
  ▶ reset/  
  ▶ shutdown/  
  ▶ slm_cmd/  
  ▶ zns_cmd/
```



Stimuli / Testing

Transaction mode

- blocking and non-blocking
- Simultaneous or sequential simulation of computational/SLM commands along with NVM, ZNS and KV commands

DEBUG ID	BDF	S R C	R W	TYPE	SQID	CQID	REG_NAME / QENTRY	CMD / REG_DATA / STS	MISC	MISC1	CID	PS DT	PRP2 / SGL1[39:32]	PRP1 / SGL1[31:24]	NSID
-----	0100	H	W	REG	----	----	SQ1TDBL	00000005	----	-----	----	---	-----	-----	-----
-----	0100	H	W	MSIX	0	----	MASK_C	00000000	----	-----	----	---	-----	-----	-----
0100000100000023	0100	D	R	IOSQ	0001	0001	0	MEM_WR	100	-----	0000	PRP	0000000000000000	0000C14338900000	00000002
0100000100000024	0100	D	R	IOSQ	0001	0001	1	_WR	0	0000	0001	PRP	0000000000000000	000009ED71C92000	00000001
0100000100000025	0100	D	R	IOSQ	0001	0001	2	EXEC_PRG	0	-----	0002	PRP	0000000000000000	0000D7322CA87000	00000004
0100000100000026	0100	D	R	IOSQ	0001	0001	3	EXEC_PRG	96	-----	0003	PRP	0000000000000000	0000832D9ACFD000	00000004
0100000100000027	0100	D	R	IOSQ	0001	0001	4	EXEC_PRG	100	-----	0004	PRP	0000000000000000	000079DF83CED000	00000004
0100000100000023	0100	D	R	PRPDW	----	----	-----	-----	-----	-----	----	---	-----	-----	-----
0100000100000023	0100	D	W	IOCO	0001	0001	0	GEN00	00005	-----	0000	---	-----	-----	-----
-----	0100	D	W	INTR	----	----	-----	-----	-----	-----	----	---	-----	-----	-----
-----	0100	H	W	MSIX	0	----	MASK_S	00000001	----	-----	----	---	-----	-----	-----
-----	0100	H	W	REG	----	----	CQ1HDBL	00000001	----	-----	----	---	-----	-----	-----
-----	0100	H	W	MSIX	0	----	MASK_C	00000000	----	-----	----	---	-----	-----	-----
0100000100000024	0100	D	R	PRPDW	----	----	-----	-----	-----	-----	----	---	-----	-----	-----
0100000100000024	0100	D	W	IOCO	0001	0001	1	GEN00	00005	-----	0001	---	-----	-----	-----
0100000100000025	0100	D	W	IOCO	0001	0001	2	GEN00	00005	-----	0002	---	-----	-----	-----
-----	0100	D	W	INTR	----	----	-----	-----	-----	-----	----	---	-----	-----	-----
-----	0100	H	W	MSIX	0	----	MASK_S	00000001	----	-----	----	---	-----	-----	-----



Coverage

- validate that DUT functions correctly under all possible scenarios
 - functional coverage, code coverage and assertion coverage

□ Comprehensive Coverage Plan

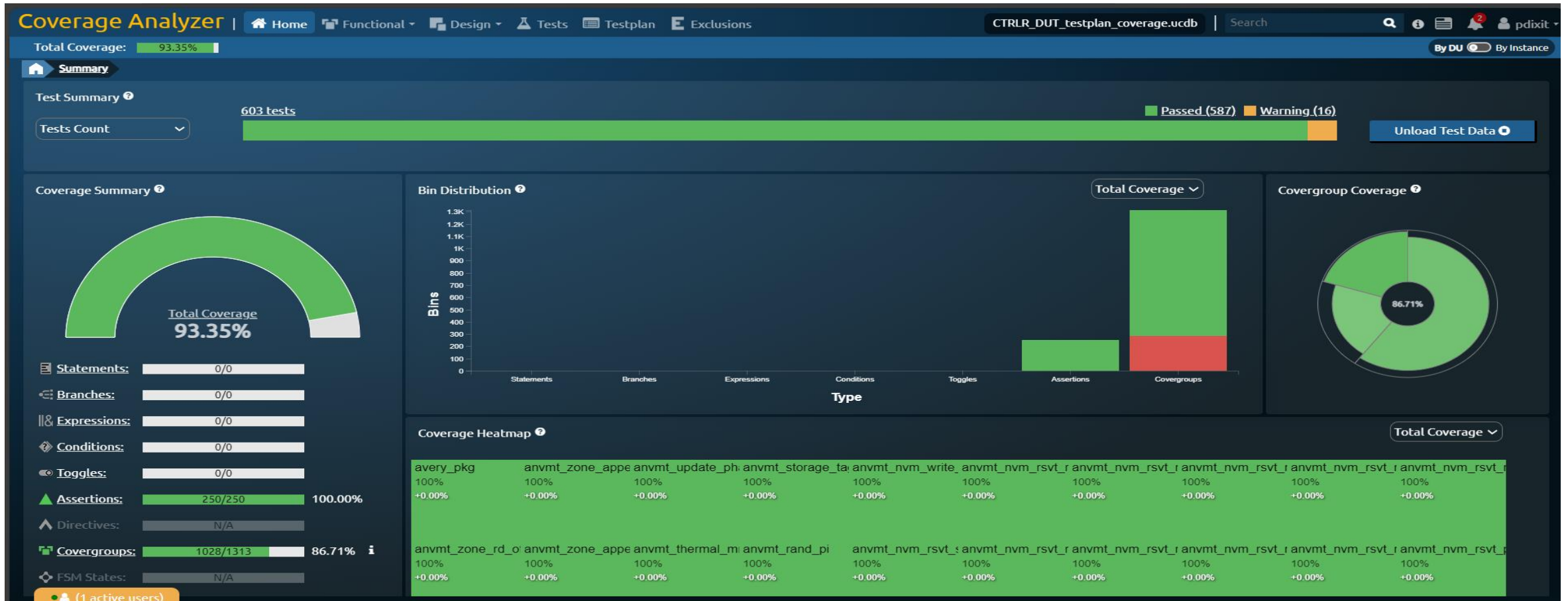
- All fields of Computational and SLM Admin, I/O commands
- Crosses with possible status code types
- Each cover point has a corresponding test in compliance test suite

□ VIQ

- Reduced coverage closure time – hole analysis, heatmaps, bin distribution
- Debugging tool – failure signature detection



Coverage



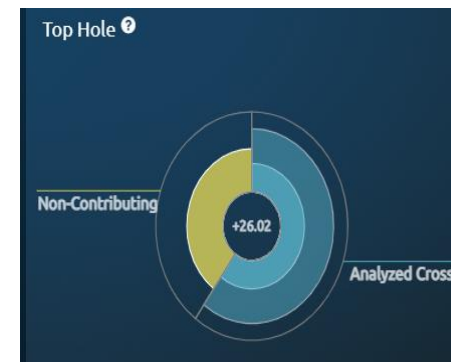
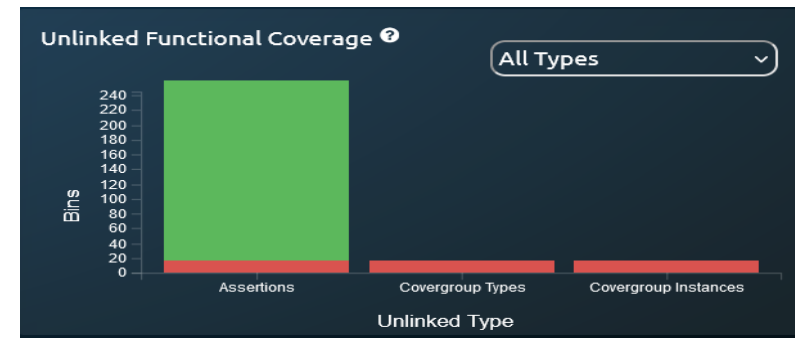
Coverage

Name	At least	Hits ↓	Bin type
auto[NVME_4_6_2]	1	126813	NORMAL_BIN
auto[NVME_4_6_1]	1	84542	NORMAL_BIN
auto[NVME_1_4_4]	1	44665	NORMAL_BIN
auto[NVME_5_3]	1	44653	NORMAL_BIN
auto[NVME_4_6_1_2_1]	1	42275	NORMAL_BIN
auto[NVME_4_6_1_2_21]	1	42271	NORMAL_BIN
auto[NVME_4_6_1_2_16]	1	42271	NORMAL_BIN
auto[NVM20_3_5_3_fig1...	1	42271	NORMAL_BIN

GAP ANALYSIS

Top Uncovered Sections

#	Name	Coverage %
11	anvmt_14_cmb_CQMMS_err	0.00%
63	anvmt_UNH_admin_cmd_1_1_11	0.00%
64	anvmt_UNH_admin_cmd_1_1_12	0.00%
66	anvmt_UNH_admin_cmd_1_1_14	0.00%
445	anvmt_boot_partition_full	0.00%



Coverage

Regression Run Details

Run Number: #29

Status: Passed

Actions: 188

Tests: 179

Passed: 179

Failed: 0

Failure Signatures: 0

Result Analysis: 0 messages

Regression Flow: Regression Navigator

Regression Time: 3m 44s

Regression Date: 2024-03-13 - 15:40:34

Total Coverage: 39.24%

Testplan Coverage: 0%

Failure Prediction Status: Disabled

Pending: 0

Launched: 0

Running: 0

Not Run: 0

Skipped: 0

Dropped: 0

Killed: 0

Timed Out: 0

Regression Actions

Group By: None

Action	Type	Test Name	Seed	Run Status	Severity	Total Coverage	Testplan Cov...	Elapsed Time	Queued Time
...rsvt_sup/execScript	test	...rsvt_sup.sv.cov_mti	1234	Passed	warning	21.62%	0%	51s	31s
...reempt/execScript	test	...preempt.sv.cov_mti	1234	Passed	warning	21.32%	0%	50s	31s
...t_report/execScript	test	...t_report.sv.cov_mti	1234	Passed	warning	21.09%	0%	51s	31s
...release/execScript	test	...release.sv.cov_mti	1234	Passed	warning	21.12%	0%	50s	30s

REGRESSION ANALYSIS

Failure Signatures

Failure Signature	Last Occurrence	Number of Tests	Number of Occurrences	Failing Since
** Warning: (vsim-3829) ...	Run 45	3	17	Run 45
** Warning: (vsim-3829) ...	Run 36	1	2	Run 36



Debugging

- identifying, isolating, and fixing bugs in large design
- hard to trace errors back to their source

- Transaction Logger
- Beat Logger



Debugging

Transaction Logger

- Debug ID associated with each command
- Print frequently required characteristics of commands

Various decoded fields
Command Specific : -
- PID, PIT, PTYPE, PSIZE ... ,etc
Generic :-
- NSID, CID, PRP ... ,etc

Name	Type	Size	Value
admin_txn	nvme_txn	-	@22376
Txn Type	string	12	NVME_TXN_SQE
Debug ID	integral	64	'h1000000000000001f
Opcode	string	17	NVME_AD_LOAD_PROG
Time	time	64	0
BDF	integral	16	'h100
Command ID	integral	16	'h5
NSID	integral	32	'h4
Program Index	integral	16	'd1
Program Type	integral	8	'hc0
Select	integral	4	'h0
Program Identifier Type	integral	3	'd0
Program Size	integral	32	'd1000
Program Identifier	integral	64	'h0
Number of Bytes	integral	32	'd0
Load Offset	integral	32	'd0
PRP Count	integral	32	'd0
PRP1	integral	64	'h58ce4ce79000

Name	Type	Size	Value
admin_txn	nvme_txn	-	@22376
Txn Type	string	12	NVME_TXN_CQE
Debug ID	integral	64	'h1000000000000001f
Opcode	string	17	NVME_AD_LOAD_PROG
Time	time	64	25327925000
BDF	integral	16	'h100
Command ID	integral	16	'h5
NSID	integral	32	'h4
Program Index	integral	16	'd1
Program Type	integral	8	'hc0
Select	integral	4	'h0
Program Identifier Type	integral	3	'd0
Program Size	integral	32	'd1000
Program Identifier	integral	64	'h0
Number of Bytes	integral	32	'd0
Load Offset	integral	32	'd0
PRP1	integral	64	'h58ce4ce79000
Completion Status (DNR)	integral	1	'h0
Completion Status (More)	integral	1	'h0
Completion Status (SCT) :	string	23	Generic Command Status
Completion Status (SC)	string	14	NVME_SUCC_CMPL



Debugging

☐ Beat Logger

- Correlate all transport transactions under single nvme_txn
- Highlights any unwanted address access

DEBUG ID	BDF	SRC	RW	TYPE	SOID	COID	REG_NAME / QENTRY	CMD / REG_DATA / STS	MISC	MISC1	CID	PS DT	PRP2 / SGL1[39:32]	PRP1 / SGL1[31:24]	NSID	ADDR
0100000000000020	0100	H	W	REG	---	---	SQ0TDBL	00000007	---	---	---	---	---	---	---	0000C00000001000
0100000000000020	0100	D	R	ASQ	---	---	7	LOAD_PRG	---	---	0006	PRP	0000000000000000	000001B1818E7000	00000004	0000D88459DE31C0
0100000000000020	0100	D	W	ACQ	---	---	7	GEN00	000008	---	0006	---	---	---	---	00009905DB8A9070
0100000000000021	0100	D	W	INTR	---	---	---	---	---	---	---	---	---	---	---	0000CE8F47053000
0100000000000021	0100	H	W	MSIX	0	---	MASK_S	00000001	---	---	---	---	---	---	---	0000C0000003000C
0100000000000021	0100	H	W	REG	---	---	CQ0HDBL	00000008	---	---	---	---	---	---	---	0000C00000001004
0100000000000021	0100	H	W	REG	---	---	SQ0TDBL	00000009	---	---	---	---	---	---	---	0000C00000001000
0100000000000021	0100	H	W	MSIX	0	---	MASK_C	00000000	---	---	---	---	---	---	---	0000C0000003000C
0100000000000021	0100	D	R	ASQ	---	---	8	GET_LG_PG	PROGL	---	0007	PRP	0000000000000000	0000E927E4F3B000	00000004	0000D88459DE3200
0100000000000021	0100	D	W	LOGP	---	---	---	---	---	---	---	---	---	---	---	0000E927E4F3B000
0100000000000021	0100	D	W	ACQ	---	---	8	GEN00	000009	---	0007	---	---	---	---	00009905DB8A9080
0100000000000021	0100	D	W	INTR	---	---	---	---	---	---	---	---	---	---	---	0000CE8F47053000
0100000000000021	0100	H	W	MSIX	0	---	MASK_S	00000001	---	---	---	---	---	---	---	0000C0000003000C
0100000000000021	0100	H	W	REG	---	---	CQ0HDBL	00000009	---	---	---	---	---	---	---	0000C00000001004
0100000000000021	0100	H	W	REG	---	---	SQ0TDBL	0000000A	---	---	---	---	---	---	---	0000C00000001000
0100000000000021	0100	H	W	MSIX	0	---	MASK_C	00000000	---	---	---	---	---	---	---	0000C0000003000C
0100000000000022	0100	D	R	ASQ	---	---	9	PRG_ACT_MNG	---	---	0008	PRP	0000000000000000	0000000000000000	00000004	0000D88459DE3240
0100000000000022	0100	D	W	ACQ	---	---	9	GEN00	00000A	---	0008	---	---	---	---	00009905DB8A9090
0100000000000022	0100	D	W	INTR	---	---	---	---	---	---	---	---	---	---	---	0000CE8F47053000
0100000000000022	0100	H	W	MSIX	0	---	MASK_S	00000001	---	---	---	---	---	---	---	0000C0000003000C
0100000000000022	0100	H	W	REG	---	---	CQ0HDBL	0000000A	---	---	---	---	---	---	---	0000C00000001004
0100000000000022	0100	H	W	REG	---	---	SQ1TDBL	00000001	---	---	---	---	---	---	---	0000C00000001008
0100000000000022	0100	H	W	MSIX	0	---	MASK_C	00000000	---	---	---	---	---	---	---	0000C0000003000C
0100000100000026	0100	D	R	IOSQ	0001	0001	0	EXEC_PRG	0	---	0000	PRP	0000000000000000	0000C14338900000	00000004	0000640033B41000
0100000100000026	0100	D	W	IOQC	0001	0001	0	GEN00	00001	---	0000	---	---	---	---	0000DEFFF9C30000
0100000100000026	0100	D	W	INTR	---	---	---	---	---	---	---	---	---	---	---	0000CE8F47053000
0100000100000026	0100	H	W	MSIX	0	---	MASK_S	00000001	---	---	---	---	---	---	---	0000C0000003000C
0100000100000026	0100	H	W	REG	---	---	CQ1HDBL	00000001	---	---	---	---	---	---	---	0000C0000000100C
0100000100000026	0100	H	W	REG	---	---	SQ1TDBL	00000002	---	---	---	---	---	---	---	0000C00000001008
0100000100000026	0100	H	W	MSIX	0	---	MASK_C	00000000	---	---	---	---	---	---	---	0000C0000003000C
0100000100000027	0100	D	R	IOSQ	0001	0001	1	EXEC_PRG	96	---	0001	PRP	0000000000000000	00006ACB69AAD000	00000004	0000640033B41040
0100000100000027	0100	D	R	PRPDW	---	---	---	---	---	---	---	---	---	---	---	00006ACB69AAD000
0100000100000027	0100	D	W	IOQC	0001	0001	1	GEN00	00002	---	0001	---	---	---	---	0000DEFFF9C30100



Performance Assessment

➤ assessing the performance of NVMe operations and Computational/SLM operations when handled concurrently

□ Performance Logger

- Latency
- Throughput
- IOPS



Performance Assessment

SUMMARY										
DEBUG ID	BDF	QID	PRIORITY	CMD	CID	TDB TIME	FSQE TIME	CQE TIME	TDB2SQE	TDB2CQE
010000000000019	0100	0000	URGENT	MEM_RNG_SET_MNG	0000	24876675000	24894925000	24926925000	18250000	50250000
01000000000001A	0100	0000	URGENT	MEM_RNG_SET_MNG	0001	24934175000	24952425000	24986175000	18250000	52000000
01000000000001B	0100	0000	URGENT	GET_LG_PG	0002	24993425000	25011675000	25059175000	18250000	65750000
01000000000001F	0100	0000	URGENT	LOAD_PROG	0005	25285425000	25310425000	25325675000	25000000	40250000
010000000000020	0100	0000	URGENT	LOAD_PROG	0006	25332925000	25351175000	25365425000	18250000	32500000
010000000000021	0100	0000	URGENT	GET_LG_PG	0007	25372675000	25390925000	25438425000	18250000	65750000
010000000000022	0100	0000	URGENT	PROG_ACT_MNG	0008	25445675000	25463925000	25478175000	18250000	32500000
010000000000028	0100	0000	URGENT	PROG_ACT_MNG	0009	25645425000	25676925000	25691175000	31500000	45750000
010000000000029	0100	0000	URGENT	PROG_ACT_MNG	000A	25645425000	25676925000	25727925000	31500000	82500000
01000000000002A	0100	0000	URGENT	GET_LG_PG	000B	25645425000	25676925000	25732175000	31500000	86750000
01000000000002B	0100	0000	URGENT	PROG_ACT_MNG	000C	25645425000	25676925000	25734925000	31500000	89500000
01000000000002C	0100	0000	URGENT	GET_LG_PG	000D	25753675000	25771925000	25819425000	18250000	65750000
01000000000002D	0100	0000	URGENT	PROG_ACT_MNG	000E	25826675000	25844675000	25858925000	18000000	32250000
01000000000002E	0100	0000	URGENT	GET_LG_PG	000F	25866175000	25884175000	25931675000	18000000	65500000
01000000000002F	0100	0000	URGENT	LOAD_PROG	0000	25938925000	25957175000	25971425000	18250000	32500000
010000000000030	0100	0000	URGENT	GET_LG_PG	0001	25978675000	25996675000	26043925000	18000000	65250000
010000000000031	0100	0000	URGENT	LOAD_PROG	0002	26051175000	26069425000	26083675000	18250000	32500000
010000000000032	0100	0000	URGENT	GET_LG_PG	0003	26091175000	26109425000	26156675000	18250000	65500000
010000000000033	0100	0000	URGENT	MEM_RNG_SET_MNG	0004	26163925000	26182175000	26196175000	18250000	32250000
010000000000034	0100	0000	URGENT	GET_LG_PG	0064	26203675000	26221925000	26244425000	18250000	40750000
010000000000035	0100	0000	URGENT	MEM_RNG_SET_MNG	0005	26251925000	26270175000	26283925000	18250000	32000000
010000000000036	0100	0000	URGENT	GET_LG_PG	0006	26291175000	26309425000	26332175000	18250000	41000000
010000010000024	0100	0001	URGENT	WR	0001	25485425000	25521925000	25616925000	36500000	131500000
010000010000025	0100	0001	URGENT	RD	0002	25485425000	25521925000	25619425000	36500000	134000000
010000010000026	0100	0001	URGENT	WR	0003	25485425000	25521925000	25623675000	36500000	138250000
01000001000006C	0100	0001	URGENT	RD	0004	28874675000	28892925000	28906675000	18250000	32000000

QID	PRIORITY	AVG TDB2SQE
0000	URGENT	18894444
0001	URGENT	27350000
0000	URGENT	18250000

IOPS		
BDF	CMD	NUM OF CMDS
0100	WR	298567
0100	RD	298567
Total		597134

THROUGHPUT		
BDF	CMD	MBPS
0100	WR	19
0100	RD	19
Total		36

TDB2CQE		
BDF	CMD	AVG. TDB2CQE
0100	WR	81777777
0100	RD	0
Average IO		40888888



Thank You !

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