Emerging Performance Tests
for
NAND Flash Based Solid State Storage

Eden Kim
CEO, Calypso Systems, Inc.
Chair, SNIA SSS Technical Working Group
info@calypsotesters.com
Outline

I. SSD Performance Behaviors
II. Issues Affecting SSD Performance Test
III. Performance Benchmarking Test Methodologies
IV. SNIA PTS Test Methodologies
V. SNIA PTS 1.0 Tests
VI. Emerging Synthetic Tests
VII. Take-Aways
I. SSD Performance Behaviors
SSD Performance is Highly Dependent on:

➤ Write History

➤ Workload Stimulus

➤ HW / SW Environment
Write History Effects
Continuous RND 4K Writes

SSD Performance States - Normalized IOPS

- D1 MLC
- D2 MLC
- D3 MLC
- D4 MLC
- D5 MLC
- D6 MLC
- D7 SLC
- D8 SLC

FOB
Transition
Steady State (desirable test range)
Workload Effects
Changing Sustained Stimuli

MLC A: XSR (Cross Stim Recovery)
(SEQ/128K-RND/4K-SEQ/128K)

SEQ/128K

SEQ/128K

RND/4K

Throughput (MB/s)

Time (Minutes)
IOPS (Log10) – RND 4K Writes over Time
Comparing PCI-e, SLC, MLC & Hybrid/SAS HDD
II. Issues Affecting SSD Performance
Factors Impacting SSD Performance

- **Write History**
  - What was previously written
  - Trim effects

- **PC Active Range**
  - Where data was previously written

- **Test Active Range**
  - Where data is currently written

- **Data Content**
  - What is the nature of the data

- **Access Pattern**
  - Manner in which data is being accessed

- **Demand Intensity**
  - How hard the app is driving the device

- **Throttling**
  - How fast is data being written vs warranty

- **Other?**
III. Performance Benchmarking Methodologies
Goals of A Good Performance Benchmark

**Repeatability**
- Common Starting Point & Procedures
- Steady State Reporting

**Applicability**
- Typical Workload Characteristics
- Sensitive to SSD Performance Issues

**Comparability**
- SSD Device Comparison
- Repeatable Ordinal Rankings

**Practicality**
- Reasonable Test Time & Effort
- Open Accessible Specification

**Verifiability**
- Audit Trail
- 3rd Party Validation
## Examples of SSD Benchmarking

<table>
<thead>
<tr>
<th>TYPE</th>
<th>EXAMPLE</th>
</tr>
</thead>
</table>
| 100% Real World     | SSD A in user’s hardware system playing user’s software; replace SSD A with SSD B  
“Use different SSDs in the exact same personal computer running your software” |
| Trace-Capture +     | Capture IO Trace on SSD A in user’s system  
Condense / Simplify IO Trace  
Replay IO Trace on SSD B in user’s same system  
“Capture my Trace on SSD A, replay a simplified Trace on SSD B in my system” |
| Trace Playback      | Standard trace capture of a typical workload on a reference system using a reference SSD  
Condense / Simplify the trace into a “Golden Trace”  
Use Golden Trace on various SSDs in the user’s system  
“Use a “Golden Trace” created by a 3d party to test SSD A & B on my system” |
| Scripted Applications | A tool that scripts application behavior in user’s system testing different SSDs  
“Play a collage of application snippets in my system on different SSDs” |
| Synthetic           | Generate specific, repeatable workloads on your system that have characteristics drawn from representative workloads to apply against different SSDs  
“Use a matrix of known test stimuli on a reference system against different SSDs and extract measurements of interest similar to your anticipated workload” |
## Benchmarking Pros & Cons

<table>
<thead>
<tr>
<th>TYPE</th>
<th>Repeatable</th>
<th>Stable</th>
<th>Applicable</th>
<th>Comparable</th>
<th>Practical</th>
<th>Accessible</th>
<th>Verifiable</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Real World</td>
<td>?</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Trace-Capture + Trace Playback</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>?</td>
<td>?</td>
<td>✗</td>
</tr>
<tr>
<td>Trace Playback</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
<td>?</td>
<td>✓</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Scripted Applications</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
<td>?</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>SYNTETICH</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
The Case for Synthetic Device Testing

- Synthetic Tests are optimal until there are Industry Standardized Trace Capture & Trace Replay Methodologies

- Properly designed Synthetic Tests **WILL** yield useful metrics

- Selecting Synthetic Metrics of Interest – The test sponsor can extract metrics that share characteristics with the user workload to allow for direct device-to-device comparison

- Use of a Reference Test Platform normalizes the influences of hardware, OS, applications and drivers when comparing SSD device performance allowing for Ordinal ranking of SSDs.
IV. SNIA PTS Test Methodologies
Performance Test Specification ("PTS")

- PTS-E & PTS-C
- Comparative Performance
- NAND Flash Based Storage
- Device Level – Individual SSDs
- Block IO – Not File System
- Enterprise & Client Class
Solid State Storage Performance Test Specification – Enterprise – V1.0

Table of Contents
Revision History ........................................................................................................................................... 2
Contributors .................................................................................................................................................. 4
Usage ............................................................................................................................................................. 5
  Disclaimer ................................................................................................................................................ 5
  Contacting SNIA ......................................................................................................................................... 5
  Intended Audience ..................................................................................................................................... 5
  Changes to the Specification ........................................................................................................................ 5
Table of Contents ......................................................................................................................................... 7
List of Tables ................................................................................................................................................. 9
List of Figures ............................................................................................................................................... 9
1 Introduction ............................................................................................................................................... 10
  1.1 Purpose ............................................................................................................................................... 10
  1.2 Background ......................................................................................................................................... 10
  1.3 Scope .................................................................................................................................................. 11
  1.4 Not in Scope ......................................................................................................................................... 11
  1.5 Disclaimer .......................................................................................................................................... 11
  1.6 Normative References .......................................................................................................................... 11
    1.6.1 Approved references ..................................................................................................................... 11
    1.6.2 References under development .................................................................................................. 11
    1.6.3 Other references ........................................................................................................................... 11
2 Definitions, symbols, abbreviations, and conventions ............................................................................ 12
  2.1 Definitions .......................................................................................................................................... 12
  2.2 Acronyms and Abbreviations .............................................................................................................. 13
  2.3 Keywords ............................................................................................................................................ 13
  2.4 Conventions ........................................................................................................................................ 13
    2.4.1 Number Conventions ................................................................................................................ 13
    2.4.2 Pseudo Code Conventions ....................................................................................................... 14
3 Key Test Process Concepts ......................................................................................................................... 15
  3.1 Steady State ........................................................................................................................................ 15
  3.2 Purge ................................................................................................................................................... 15
  3.3 Preconditioning ................................................................................................................................... 15
  3.4 Active Range ....................................................................................................................................... 16
  3.5 Data Patterns ...................................................................................................................................... 16
  3.6 Multiple Thread Guideline ................................................................................................................ 16
  3.7 Caching .............................................................................................................................................. 16
4 Overview of Common Test Flow ................................................................................................................. 17
5 Common Reporting Requirements ............................................................................................................ 18
  5.1 General ............................................................................................................................................... 18
  5.2 Test System Hardware ......................................................................................................................... 18
  5.3 Test System Software .......................................................................................................................... 18
  5.4 Device Under Test .............................................................................................................................. 18
6 Test Tool Guidelines .................................................................................................................................. 19

• Terminology
• Metrics
• Methodologies
• Tests
• Reporting Requirements
• Reference Test Environment
SSSI Reference Test Platform
Common Hardware & Software Environment

- Intel S5520HC
- Intel W5580, 3.2 GHz, Quad-core CPU
- 12GB, 1333MHz, ECC DDR3 RAM
- LIS9212-4e4i 6Gb/s SAS HBA
- Calypso Test Suite (CTS) v6.5
- Calypso RTP Backend v1.5
- PCI-e Gen-II 8 Lane
- Intel ICH10R 3Gb/s SATA
- CentOS 5.5
Basic Test Flow

SSS PTS TEST SEQUENCE

- Purge
- Precondition
- Test
- Collect & Report
Key Concepts & Test Steps

1. **Purge**
   - Secure Erase, Sanitize, Format Unit, other proprietary methods

2. **Set Conditions**
   - Set user selectable test parameters, such as Active Range, Data Pattern, Demand intensity

3. **Pre-Condition**
   - Workload Independent
   - Workload Dependent

4. **Run Until SS**
   - Reiterate loops until Steady State is reached, or run to a prescribed maximum number of loops

5. **Collect Data**
   - Collect data from Steady State Measurement Window

6. **Generate Reports**
   - Use standard report formats and include required and optional elements
PTS Test Pseudo Code Conventions

PTS-E & PTS-C Test Loops are specified in “Pseudo Code”

IOPS Test Loop Pseudo Code example: **56 Point R/W Mix x Block Size Test Loop**

For (R/W Mix % = 100/0, 95/5, 65/35, 50/50, 35/65, 5/95, 0/100) For (Block Size = 1024KiB, 128KiB, 64KiB, 32KiB, 16KiB, 8KiB, 4KiB, 0.5KiB)

- Execute random IO, per (R/W Mix %, Block Size), for 1 minute
- Record Ave IOPS(R/W Mix%, Block Size)

This loop is executed as follows:

Set R/W Mix% to 100/0
Set Block Size to 1024KiB
Execute random IO...
Record Ave IOPS...
Set Block Size to 128KiB
Execute...
Record...
...
Set Block Size to 0.5KiB
Execute...
Record...
Set R/W Mix% to 95/5
Set Block Size to 1024KiB
Execute...
Record...
...

Beginning of Outer Loop 1 (R/W Mix 100/0)
Run R/W Mix 100/0 for all BS beginning w/ 1024K to 0.5K

End of Loop 1

Beginning of Outer Loop 2 (R/W Mix 95/5)
Run R/W Mix 95/5 for all BS beginning w/ 1024K to 0.5K

NOTE: 1 Round = 7 R/W Mixes x 8 BS for 1 min ea = 56 minutes
PTS-E: IOPS Test Pseudo Code

1) Purge the device. (Note: Active Range and other Test Parameters are not applicable to Purge step; any values can be used and none need to be reported.)

2) Workload Independent Preconditioning
   a) Set OIO/Thread, Thread Count, Data Pattern, per Test Operator Choice
   b) Write 2X User Capacity w/ 128KiB sequential writes.

3) Set test parameters and record for later reporting
   a) Device write cache = Disabled
   b) OIO/Thread: Test Operator Choice
   c) Thread Count: Test Operator Choice
   d) Data Pattern: Required = Random, Optional = Test Operator Choice

4) Run the following test loop until Steady State is reached, or maximum of 25 Rounds:
   For (R/W Mix % = 100/0, 95/5, 65/35, 50/50, 35/65, 5/95, 0/100)
   For (Block Size = 1024KiB, 128KiB, 64KiB, 32KiB, 16KiB, 8KiB, 4KiB, 0.5KiB)
   - Execute random IO, per (R/W Mix %, Block Size), for 1 minute
   - Record Ave IOPS(R/W Mix%, Block Size)

Use IOPS(R/W Mix% = 0/100, Block Size = 4KiB) to detect Steady State.
If Steady State is not reached by Round x<=25, then the Test Operator shall either continue running the test until Steady State is reached, or may stop the test at Round x. The Measurement Window is defined as Round x-4 to Round x.

5) Process and plot the accumulated Rounds data, per report guidelines in next section,
PTS-E IOPS Test: Block Size Sequence

Test Duration (Min) vs. Block Size (KiB)

- SEQ/128KiB Pre-Conditioning
- RW=100/0
- RW=95/5
- RW=65/35

WIPC → WDPC

Block Size (KiB) vs. Block Size (KiB)

- 1024
- 128
- 64
- 32
- 16
- 8
- 4
- 0.5
Block Size Sequence: IOPS Test Loop
PTS-E: Throughput Test Pseudo Code

For (Block Size = 1024KiB, 64KiB, 8KiB, 4KiB, 0.5KiB)

1) Purge the device. (Note: Active Range and other Test Parameters are not applicable to Purge step; any values can be used and none need to be reported.)

2) Set test parameters and record for later reporting
   a) OIO/Thread: Test Operator Choice
   b) Thread Count: Test Operator Choice
   c) Data Pattern: Required = Random, Optional = Test Operator Choice

3) Run the following until Steady State is reached, or maximum of 25 Rounds:

   For (R/W Mix % = 100/0, 0/100)
   - Execute **sequential IO**, per (R/W Mix%, Block Size), for 1 minute
   - Record Ave MB/s (R/W Mix%, Block Size)

   Use Ave MB/s(RW Mix%, Block Size) to detect Steady State.

   If Steady State is not reached by Round \( x \leq 25 \), then the Test Operator shall either continue running the test until Steady State is reached, or may stop the
PTS-E: Latency Block Size Sequencing

For (ActiveRange(0:100), optional ActiveRange(Test Operator Choice))

1) Purge the device. (Note: Active Range and other Test Parameters are not applicable to Purge step; any values can be used and none need to be reported.)

2) Workload Independent Preconditioning
   a) Set OIO/Thread, Thread Count, Data Pattern, per Test Operator Choice
   b) Write 2X User Capacity w/ 128KiB sequential writes.

3) Set test parameters and record for later reporting
   a) OIO/Thread: 1
   b) Thread Count: 1
   c) Data Pattern: Required = Random, Optional = Test Operator Choice

4) Run the following test loop until Steady State is reached, or maximum of 25 Rounds:
   For (R/W% = 100/0, 65/35, 0/100)
   For (Block Size = 8KiB, 4KiB, 0.5KiB)
   - Execute random IO per (R/W%, Block Size), for 1 minute
   - Record Max and Ave Latency (R/W%, Block Size)
   Use Ave Latency (R/W Mix%=0/100, Block Size=4KiB) to detect Steady State.

   If Steady State is not reached by Round x<=25, then the Test Operator shall either continue running the test until Steady State is reached, or may stop the
Enterprise Latency RW/BS Sequence
Steady State Window

Tracking Variable = RND/4KiB IOPS

Measurement Window
Steady State Measurement Window

Steady State Measurement Windows (Rounds 12-16)

- IOPS
- Average
- 110% of Average
- 90% of Average
- Slope

Data Excursion
Slope Excursion
10% of Average
20% of Average

IOPS

Round

2011 Storage Developer Conference. © Calypso Systems, Inc.. All Rights Reserved.
REPORT HEADERS – Detailed Test Conditions

SS CONVERGENCE – Tracking Performance Settling

SS DETERMINATION – Tracking Dependent Variable

SS WINDOW – Defining SS Measurement Window

RESULTS – Standardized Tables & Plots
<table>
<thead>
<tr>
<th>Test Run Date:</th>
<th>02/19/2011 03:49 AM</th>
<th>Report Run Date:</th>
<th>03/03/2011 08:47 AM</th>
</tr>
</thead>
</table>

### IOPS (REQUIRED) - Report Page

**SNIA SSS TWG:** Solid State Storage Performance Test Specification (PTS)

### Device Under Test (DUT)

<table>
<thead>
<tr>
<th>WDC SSC-D0256SC-</th>
<th>Western Digital</th>
<th>8.1 IOPS Test - REQUIRED</th>
<th>Calypso Systems Inc</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N: CB443C8131032154F405</td>
<td>Purge</td>
<td>Security Erase</td>
<td></td>
</tr>
<tr>
<td>DUT I/F</td>
<td>SATA 3Gb/s</td>
<td>Pre-Conditioning</td>
<td></td>
</tr>
<tr>
<td>SYS I/F</td>
<td>LSI 9212-4e4i int. SAS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test HW</td>
<td>Calypso RTP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test SW</td>
<td>CTSv6.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Test Loop Parameters

<table>
<thead>
<tr>
<th></th>
<th>Test Loop Parameters</th>
<th>Steady State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workload Dep.</td>
<td>2X SEQ/128KB</td>
<td>REQUIRED:</td>
</tr>
<tr>
<td>Full IOPS Loop</td>
<td></td>
<td>Data Pattern</td>
</tr>
<tr>
<td></td>
<td>Tester's Choice:</td>
<td>OIO/Thread</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thread Count</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Convergence</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rounds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Active Range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>REQ:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPT:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BS=0.5 KiB</th>
<th>BS=4 KiB</th>
<th>BS=8 KiB</th>
<th>BS=16 KiB</th>
<th>BS=32 KiB</th>
<th>BS=64 KiB</th>
<th>BS=128 KiB</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.64</td>
<td>52.68</td>
<td>31.00</td>
<td>29.56</td>
<td>13.54</td>
<td>11.67</td>
<td>8.90</td>
</tr>
<tr>
<td>68.70</td>
<td>49.93</td>
<td>21.10</td>
<td>12.51</td>
<td>11.83</td>
<td>8.93</td>
<td>2.25</td>
</tr>
<tr>
<td>41.33</td>
<td>38.00</td>
<td>20.90</td>
<td>13.20</td>
<td>9.16</td>
<td>7.82</td>
<td>2.38</td>
</tr>
<tr>
<td>47.42</td>
<td>38.36</td>
<td>25.81</td>
<td>15.23</td>
<td>10.08</td>
<td>8.02</td>
<td>1.59</td>
</tr>
<tr>
<td>45.02</td>
<td>30.47</td>
<td>44.28</td>
<td>20.42</td>
<td>17.91</td>
<td>13.14</td>
<td>10.22</td>
</tr>
</tbody>
</table>

**Device Under Test (DUT)**

- **Western Digital**
- **8.1 IOPS Test - REQUIRED**
- **Calypso Systems Inc**

**DUT Preparation**

- Purge
- Security Erase

**Test Loop Parameters**

- 2X SEQ/128KB
- Full IOPS Loop

**Steady State**

- Convergence: YES
- Rounds: 4-8
- Active Range
- REQ: 100%
- OPT: N/A
### 8.1.1 Steady State Convergence Plot – All Block Sizes

**Device Under Test (DUT):** YESC300-EEFDDAC256M

**Pre-Conditioning:**
- Micron
- Client IOPS Test - REQUIRED
- Calypso Systems Inc.

**Test HW:** Calypso RTP

**Test SW:** CTSv6.5

**Workload:**
- Independent
- 2X SEQ/128 KiB

**Workload Dep.:**
- 7603.58
- 6219.06
- 5130.82
- 4450.97
- 3971.94
- 4703.62

**Active Range:**
- N/A

**OIO/Thread:**
- 8.1

**Full IOPS Loop:**
- Thread Count: 2

**Test Run Date:** 4/24/10

**Report Run Date:** 6/13/10

---

**Graph:**
- BS=0.5 KiB
- BS=4 KiB
- BS=8 KiB
- BS=16 KiB
- BS=32 KiB
- BS=64 KiB
- BS=128 KiB

**X-axis:** Round

**Y-axis:** IOPS
SS Determination

8.1.2 Steady State Measurement Window

- IOPS
- Average
- 110% Average
- 90% Average
- Slope

Round
0 2 4 6 8 10 12 14 16 18 20
IOPS
0 2,000 4,000 6,000 8,000 10,000 12,000 14,000 16,000 18,000 20,000

Device Under Test (DUT)
Micron 8.1 Client IOPS Test - REQUIRED Calypso Systems Inc.

Key Setup Data DUT Preparation

Pre-Conditioning Data Pattern

Test Loop Parameters Steady State

Client IOPS (REQUIRED) - Report Page

SNIA SSS TWG: Solid State Storage Performance Test Specification (PTS)

Tester's Choice: Active Range

Test HW
Calypso RTP

OIO/Thread
RND
Rounds
0.8
16

Test SW
CTSv6.5

Workload Dep.
Full IOPS Loop

Thread Count
2

OPT:

Test Run Date:
4/24/10

Report Run Date:
6/13/10

SYS I/F
LSI 9212-4e4i int. SAS

Workload
Independent
2X SEQ/128 KiB

C300-EEFDDAC256M
Purge
Security Erase
REQUIRED: Convergence

Device Under Test (DUT)
Micron 8.1 Client IOPS Test - REQUIRED Calypso Systems Inc.

Key Setup Data DUT Preparation

Pre-Conditioning Data Pattern
### 8.1.4 Client IOPS - ALL RW Mix & BS – Tabular Data

<table>
<thead>
<tr>
<th>Block Size (KiB)</th>
<th>0 / 100</th>
<th>5 / 95</th>
<th>65 / 35</th>
<th>05 / 50</th>
<th>35 / 65</th>
<th>95 / 5</th>
<th>100 / 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1,122.3</td>
<td>1,162.2</td>
<td>1,654.6</td>
<td>1,965.6</td>
<td>2,717.7</td>
<td>11,970.0</td>
<td>29,860.1</td>
</tr>
<tr>
<td>8</td>
<td>3,147.0</td>
<td>2,896.6</td>
<td>3,044.4</td>
<td>3,454.4</td>
<td>3,779.3</td>
<td>13,005.8</td>
<td>29,876.3</td>
</tr>
<tr>
<td>8</td>
<td>1,584.9</td>
<td>1,589.7</td>
<td>2,055.0</td>
<td>2,238.9</td>
<td>2,898.1</td>
<td>11,568.2</td>
<td>21,723.1</td>
</tr>
<tr>
<td>16</td>
<td>765.8</td>
<td>786.3</td>
<td>1,028.1</td>
<td>1,272.6</td>
<td>1,604.9</td>
<td>6,208.3</td>
<td>12,482.5</td>
</tr>
<tr>
<td>32</td>
<td>392.7</td>
<td>401.0</td>
<td>525.8</td>
<td>652.7</td>
<td>963.8</td>
<td>4,129.6</td>
<td>7,011.6</td>
</tr>
<tr>
<td>64</td>
<td>196.4</td>
<td>205.9</td>
<td>291.3</td>
<td>352.3</td>
<td>565.4</td>
<td>2,372.7</td>
<td>3,791.5</td>
</tr>
<tr>
<td>128</td>
<td>92.5</td>
<td>97.1</td>
<td>139.9</td>
<td>185.4</td>
<td>377.9</td>
<td>1,410.2</td>
<td>2,015.3</td>
</tr>
<tr>
<td>1024</td>
<td>16.4</td>
<td>16.5</td>
<td>23.3</td>
<td>27.3</td>
<td>90.8</td>
<td>191.4</td>
<td>266.7</td>
</tr>
</tbody>
</table>
IOPS 2D Plot

8.1.5 Client IOPS - ALL RW Mix & BS - 2D Plot

- Test Loop Parameters
  - Purge: REQUIRED
  - Security Erase: REQUIRED

- Device Under Test (DUT)
  - Micron 8.1 Client IOPS Test - REQUIRED Calypso Systems Inc.

- Test HW
  - SYS I/F: LSI 9212-4e4i int. SAS
  - Tester's Choice: DUT I/F
    - SATA 6Gb/s

- Pre-Conditioning
  - RND

- Workload
  - Independent
  - 2X SEQ/128 KiB

- Data Pattern Rounds
  - OIO/Thread

- Convergence
  - YES

- OPT:
  - N/A

- CTSv6.5

- Thread Count

- Rev.
  - 0.8

- Test Run Date:
  - 4/24/10

- Report Run Date:
  - 6/13/10

- Steady State
  - Active Range

- IOPS vs. Block Size (KiB) Graph:
  - Y-axis: IOPS
  - X-axis: Block Size (KiB)
  - Lines represent different read/write mix ratios (e.g., 0/100, 5/95, 65/35, 50/50, 35/65, 95/5, 100/0)

- Key Set Up Data
  - Pre-Conditioning

- Key Set Up Data
  - Pre-Conditioning

- Key Set Up Data
  - Pre-Conditioning

- Key Set Up Data
  - Pre-Conditioning

- Key Set Up Data
  - Pre-Conditioning
8.1.6 Client IOPS - ALL RW Mix & BS - 3D Columns

- **REQ:**
  - Test SW
    - CTSv6.5
  - Workload Dep.
    - Full IOPS Loop
  - Thread Count
    - 2

- **OPT:**
  - SYS I/F
    - LSI 9212-4e4i int. SAS
  - Workload
    - Independent
    - 2X SEQ/128 KiB
    - Tester's Choice: Active Range
  - Test HW
    - Calypso RTP
    - OIO/Thread
      - 16
  - YES
  - DUT I/F
    - SATA 6Gb/s
  - Pre-Conditioning Data Pattern
    - RND
  - Rounds
    - 10-14

- **C300-EEFDDAC256M**
  - Purge
    - Security Erase
  - REQUIRED: Convergence

**Device Under Test (DUT):**
- Micron

**Key: Set Up Data DUT Preparation Test Loop Parameters Steady State**

**SNIA SSS TWG:** Solid State Storage Performance Test Specification (PTS) Rev.

**Test Run Date:**
- 4/24/10

**Report Run Date:**
- 6/13/10
V. SNIA PTS 1.0 Tests
## PTS-E vs PTS-C

<table>
<thead>
<tr>
<th>Item / Parameter</th>
<th>PTS-E</th>
<th>PTS-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workload Class</td>
<td>Enterprise</td>
<td>Client</td>
</tr>
<tr>
<td>Pre Conditioning</td>
<td>100% LBA Range</td>
<td>100% &amp; 75% LBA Range</td>
</tr>
<tr>
<td>Test Range</td>
<td>100% LBA Range</td>
<td>Limited Test 8GB &amp; 16GB</td>
</tr>
<tr>
<td>Payload Segmentation</td>
<td>Contiguous</td>
<td>Non Contiguous Randomly Distributed</td>
</tr>
<tr>
<td>PTS 1.0 Tests</td>
<td>WSAT, IOPS, TP, LAT</td>
<td>IOPS, TP, LAT</td>
</tr>
</tbody>
</table>
V(a) - SNIA PTS-E 1.0
Enterprise Workload Tests
# PTS-E 1.0: Write Saturation

## RND/4K Write Saturation

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Determines how the DUT responds to continuous RND/4K writes from a PURGED FOB state</th>
</tr>
</thead>
</table>

### Test Setup

<table>
<thead>
<tr>
<th>Preconditioning</th>
<th>None</th>
</tr>
</thead>
</table>
| **Test**        | After PURGE, continuously apply the random 4K writes until the earlier of:  
|                 | 1. 4X User capacity has been written  
|                 | 2. 24 Hours |
PTS-E 1.0: Write Saturation

MLC WSAT
PTS-E 1.0: Write Saturation

SLC WSAT

IOPS vs TGW - LIN

SLC WSAT - Continuous RND 4K W from FOB

IOPS vs Normalized Capacity (X User Capacity)
PTS-E 1.0: Write Saturation

PCI-e WSAT

IOPS vs TGW - LIN

PCI-E WSAT - Continuous RND 4K W from FOB

IOPS

PCI - A  PCI - B  PCI - C

0.0  1.0  2.0  3.0  4.0  5.0  6.0  7.0  8.0  9.0
**PTS-E 1.0: IOPS**

**Random IOPS At Various (R/W Mix, Block Size) Pairs**

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Measure the average Steady State IOPS at each of the specified R/W Mix and Block Size combination using the entire drive LBA Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Setup</strong></td>
<td><strong>Preconditioning</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Test</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PTS-E 1.0: IOPS

RND IOPS SLC A – R/W Mix x IOPS 3D BAR

![Graph showing SLC A - IOPS vs BS & RW Mixes](image)
PTS-E 1.0: IOPS

Comparison (3) SLC – Selected RND 4K x 100% R / W
## PTS-E 1.0: Throughput

### Sequential Throughput At Various Block Sizes

<table>
<thead>
<tr>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure Steady State IOPS and MB/s performance at each of the specified R/W Mix and Block Size combinations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Setup</th>
<th>Preconditioning</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WIPC: 2X Capacity SEQ/128K</td>
<td>After sequential pre-conditioning, continuously apply sequential 100% read and 100% write stimulus using each of the prescribed Block Sizes to all available LBAs until Steady State is reached. Then PURGE the device and proceed to the next Block Size.</td>
</tr>
<tr>
<td></td>
<td>WDPC: SEQ Read and Write at each Block Size</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• R/W Mix=[100/0, 0/100]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• BS= [0.5, 4, 8, 64, 1024]K</td>
</tr>
</tbody>
</table>
PTS-E 1.0: Throughput

SEQ TP SLC

THROUGHPUT Comparison - 100% SEQ R/W

Steady State - LARGER Number is Better

Throughput (MB/s)

Block Size (KB)

0.5 4 8 64 1024

SLC A SL C B SLC C
# PTS-E 1.0: Latency

## IOPS and Average Response Time At Single Outstanding IO

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Measure the Steady State average IOPS and Response Times at each of the specified R/W Mix and Block Size combination using total outstanding IO of one</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Test Setup</th>
<th>Preconditioning</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WIPC: 2X Capacity SEQ/128K</td>
<td>After sequential pre-conditioning, continuously apply the prescribed IO Mixes and Block Sizes using all available LBAs until Steady State is reached using Thread Count=1 and OIO/Thread=1.</td>
</tr>
<tr>
<td></td>
<td>WPC: entire Latency Test Loop</td>
<td>• R/W Mix=[100/0, 65/35, 0/100]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• BS= [0.5, 4, 8]K</td>
</tr>
</tbody>
</table>
PTS-E 1.0: Latency

SLC - AVE  Latency RND 4K: 100% R / 65:35 / 100% W

![Graph showing SLC AVE Latency 4K results](image-url)
PTS-E 1.0: Latency

SLC - MAX Latency RND 4K: 100% R / 65:35 / 100% W

RND 4K 100% R / 65:35 R/W / 100% W

Lower value is better.

RTP 2.0 / CTS 6.5
SNIA PTS 1.0 COMPLIANT
APRIL 2011
V(b) SNIA PTS-C 1.0
Client Workload Tests
**PTS-C 1.0: IOPS**

Random IOPS At Various (R/W Mix, Block Size) Pairs

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Measure the average IOPS at each of the specified R/W Mix and Block Size combination using a limited region of the drive</th>
</tr>
</thead>
</table>
| Preconditioning | WIPC: 2X Capacity SEQ/128K  
WDPC: entire IOPS Test Loop |
| Test Setup | After sequential pre-conditioning, continuously apply the prescribed IO Mixes and Block Sizes until Steady State is reached using the following parameters: |
| Test |  
- Active Range = [100%, 75%]  
- Active Amount = [8G, 16G]  
- Active Amount to be evenly distributed over 2048 segments; the segments are randomly distributed over the entire drive  
- R/W Mix=[100/0, 95/5, 65/35, 50/50, 35/65, 5/95, 0/100]  
- BS= [0.5, 4, 8, 16, 32, 64, 128, 1024]K |
### PTS-C 1.0: IOPS

#### RND IOPS MLC A – R/W Mix x IOPS TABLE

**Test Run Date:** 12/14/2010 12:39 AM  
**Report Run Date:** 12/31/2010 04:12 PM

---

### MFRG A - 8.1 Client IOPS Test - REQUIRED

<table>
<thead>
<tr>
<th>Device Under Test (DUT)</th>
<th>MFRG A</th>
<th>8.1 Client IOPS Test - REQUIRED</th>
<th>Calypso Systems Inc</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC-123-FFF</td>
<td>Purge</td>
<td>Security Erase</td>
<td>Steady State</td>
</tr>
<tr>
<td>S/N: 000000000103900011845</td>
<td>Pre-Conditioning</td>
<td>2X SEQ/128KB</td>
<td>Convergence: YES</td>
</tr>
<tr>
<td>DUT I/F: SATA 6Gb/s</td>
<td></td>
<td></td>
<td>Rounds: 1-5</td>
</tr>
<tr>
<td>SYS I/F: LSI 9212-4e4i int. SAS</td>
<td>Workload Independent</td>
<td></td>
<td>Active Range: 100%</td>
</tr>
<tr>
<td>Test HW: Calypso RTP</td>
<td>Workload Dep.</td>
<td>Full IOPS Loop</td>
<td>OPT: N/A</td>
</tr>
<tr>
<td>Test SW: CTSv6.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

### 8.1.4 Client IOPS - ALL RW Mix & BS – Tabular Data

#### Block Size (KiB) vs Read / Write Mix %

<table>
<thead>
<tr>
<th>Block Size (KiB)</th>
<th>0/100</th>
<th>5/95</th>
<th>65/35</th>
<th>50/50</th>
<th>35/65</th>
<th>95/5</th>
<th>100/0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1,122.3</td>
<td>1,162.2</td>
<td>1,654.6</td>
<td>1,965.6</td>
<td>2,717.7</td>
<td>11,970.0</td>
<td>29,860.1</td>
</tr>
<tr>
<td>4</td>
<td>3,147.0</td>
<td>2,896.6</td>
<td>3,044.4</td>
<td>3,454.4</td>
<td>3,779.3</td>
<td>13,005.8</td>
<td>29,876.3</td>
</tr>
<tr>
<td>8</td>
<td>1,584.9</td>
<td>1,589.7</td>
<td>2,055.0</td>
<td>2,238.9</td>
<td>2,898.1</td>
<td>11,568.2</td>
<td>21,723.1</td>
</tr>
<tr>
<td>16</td>
<td>765.8</td>
<td>786.3</td>
<td>1,028.1</td>
<td>1,272.6</td>
<td>1,604.9</td>
<td>6,208.3</td>
<td>12,482.5</td>
</tr>
<tr>
<td>32</td>
<td>392.7</td>
<td>401.0</td>
<td>525.8</td>
<td>652.7</td>
<td>963.8</td>
<td>4,129.6</td>
<td>7,011.6</td>
</tr>
<tr>
<td>64</td>
<td>196.4</td>
<td>205.9</td>
<td>291.3</td>
<td>352.3</td>
<td>565.4</td>
<td>2,372.7</td>
<td>3,791.5</td>
</tr>
<tr>
<td>128</td>
<td>92.5</td>
<td>97.1</td>
<td>139.9</td>
<td>185.4</td>
<td>377.9</td>
<td>1,410.2</td>
<td>2,015.3</td>
</tr>
<tr>
<td>1024</td>
<td>16.4</td>
<td>16.5</td>
<td>23.3</td>
<td>27.3</td>
<td>90.8</td>
<td>191.4</td>
<td>266.7</td>
</tr>
</tbody>
</table>
PTS-C 1.0: IOPS

Comparison (3) MLC – Selected RND 4K x 100% R / W

Steady State - RND 4K IOPS
100% W / 65:35 R/W
Higher value is better

- MLC A: 6,121
- MLC B: 152
- MLC C: 3,245

2011 Storage Developer Conference. © Calypso Systems, Inc.. All Rights Reserved.
## PTS-C 1.0: Throughput

### Large Block Sequential Throughput

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Measure Steady State IOPS and MB/s performance using 1024K block size</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Test Setup</th>
<th>Preconditioning</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIPC: 2X Capacity SEQ/128K</td>
<td>After sequential pre-conditioning, continuously apply sequential 100% read and 100% write stimulus at 1024K</td>
<td></td>
</tr>
<tr>
<td>WDPC: SEQ Read and Write at 1024K</td>
<td>• R/W Mix=[100/0, 0/100]</td>
<td>• BS= [1024]K</td>
</tr>
</tbody>
</table>
PTS-C 1.0: Throughput

Large Block Sequential Throughput MLC

Throughput - Steady State
SEQ 1MB - 100% W / 100% R

Higher value is better

- MLC A: 416.9 MB/s
- MLC B: 267.2 MB/s
- MLC C: 264.3 MB/s

RTP 2.0 / CTS 6.5
SNIA PTS 1.0 COMPLIANT
FEBRUARY 2011

100% READS
100% WRITES
### Purpose

Measure the Steady State average IOPS and Response Times at each of the specified R/W Mix and Block Size combination using total outstanding IO of one.

### Test Setup

<table>
<thead>
<tr>
<th>Preconditioning</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIPC: 2X Capacity SEQ/128K</td>
<td>After sequential pre-conditioning, continuously apply the prescribed IO Mixes and Block Sizes using all available LBAs until Steady State is reached using Thread Count=1 and OIO/Thread=1.</td>
</tr>
<tr>
<td>WDPC: entire Latency Test Loop</td>
<td>• R/W Mix=[100/0, 65/35, 0/100]</td>
</tr>
<tr>
<td></td>
<td>• BS=[0.5, 4, 8]K</td>
</tr>
</tbody>
</table>
PTS-C 1.0: Latency

MLC - AVE Latency RND 4K: 100% R / 65:35 / 100% W

MLC AVE LATENCY 4K
RND 4K 100% R / 65:35 R/W / 100% W

Lower value is better
PTS-C 1.0: Latency

MLC - MAX Latency RND 4K: 100% R / 65:35 / 100% W

MLC MAX LATENCY 4K
RND 4K 100% R / 65:35 R/W / 100% W

Lower value is better

msec

MC A 1.60
MLC B 1.63
MLC C 1.19
MLC D 206.56
157.37
157.18
100% READS

100% WRITES

65:35 R/W

RTP 2.0 / CTS 6.5
SNIA PTS 1.0 COMPLIANT
APRIL 2011
VI. Emerging Synthetic Tests
“Performance” beyond IOPS, TP....
There are other more subtle, but equally important performance metrics.

EXAMPLE:

RESPONSE TIME STATISTICS
How well-behaved is the response time statistics?

DEMAND INTENSITY
How hard can I drive the SSD while maintaining reasonable response times?

CROSS STIMULUS RECOVERY
How does the SSD respond to change between sustained stimulus?

HOST IDLE TIME RESPONSE
How does the SSD do during I/O idle time?
### Response Time Histogram

**AVE & MAX Response Times do not tell the whole story**

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Observe Steady State Response Time Frequency and Distribution</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Test Setup</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preconditioning</strong></td>
<td>Purge, RND/4K Writes</td>
</tr>
<tr>
<td><strong>Test</strong></td>
<td>Capture very IO’s completion time within a specified time duration and sort into specified bins</td>
</tr>
</tbody>
</table>
Response Time Histogram
(10 Min at RND/4K SS)
Response Time Histogram

(10 Min at RND/4K SS)
Response Time Histogram
(10 Min at RND/4K SS)
## IOPS Demand Intensity

### RND/4K

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Determines how the DUT responds to increasing demand from Host</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Test Setup</th>
<th>SNIA E-PTS IOPS to Steady State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preconditioning</td>
<td>Vary Total Outstanding IO (TOIO)</td>
</tr>
<tr>
<td></td>
<td>Measure RND4K IOPS Average Response Time (ART) for one minutes each IO</td>
</tr>
</tbody>
</table>
RND/4K Read Demand Intensity (E-SLC)
RND/4K Read Demand Intensity (C-MLC)
# Cross Stimulus Response

**SEQ/128K → RND/4K → SEQ/128K**

## Purpose
Determines how the DUT responds to sudden switch in stimulus to and from sustained large block sequential writes to small block random writes.

## Test Setup

<table>
<thead>
<tr>
<th>Preconditioning</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>PURGE</td>
<td>Write SEQ/128K</td>
</tr>
<tr>
<td></td>
<td>Write RND/4K</td>
</tr>
<tr>
<td></td>
<td>Write SEQ/128K</td>
</tr>
<tr>
<td></td>
<td>Capture IOPS and ART</td>
</tr>
</tbody>
</table>
Cross Stimulus Recovery:

**C-MLC**
- XSR (SEQ/128K-RND/4K-SEQ/128K) TP vs Time
- Throughput (MB/s)
- Time (Minutes)

**E-SLC**
- P2 TP vs Time
- Throughput (MB/s)
- Time (Minutes)
Cross Stimulus Recovery:

![Graphs showing cross stimulus recovery results for different write patterns and block sizes.](image-url)
# Host Idle Test

## RND/4K Write Sat. with Wait States

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Determines how the DUT responds to Host IO idle period amidst continuous IO</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Preconditioning</th>
<th>SNIA E-PTS IOPS till Steady State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Setup</td>
<td>Cease IOs for a various amount of time between segments of continuous RND/4K writes:</td>
</tr>
<tr>
<td></td>
<td>Wait State 0: Write/Idle=5s/0s</td>
</tr>
<tr>
<td></td>
<td>Wait State 1: Write/Idle=5s/5s</td>
</tr>
<tr>
<td></td>
<td>Wait State 5: Write/Idle=5s/25s</td>
</tr>
</tbody>
</table>
Host Idle Test (with Wait States)

RND/4K
VII. Take-Aways
SSD Performance is highly dependent on the test hardware and software environment, write history and workload stimulus.

Repeatable, Synthetic test allows device-to-device SSD comparison.

SNIA PTS-E & PTS-C provide industry standardized performance test.

Device Level Synthetic test metrics that share characteristics with user’s workloads of interest can be extracted for comparison.

Emerging Synthetic Tests attempt to capture characteristics of Enterprise and Client workloads.

Repeatable, reliable and comparable device level tests run in a Reference Test Environment are necessary to accurately compare SSD device performance.