

Contents

List of Figures	xix
List of Tables	xxvii
Preface	xxix
Foreword	xxxii
Acknowledgments	xxxii
Section I. SAS Architecture and Concepts	1
1. Introduction to SAS	3
1.1 What is Serial Attached SCSI?	3
1.2 A Brief History of SCSI	3
1.3 Why Serial Attached SCSI?	5
1.3.1 SAS Roadmap	7
1.3.2 What SAS Isn't	7
1.4 The SAS and SCSI Architectures	8
1.4.1 SAS Initiator Devices	9
1.4.2 SAS Target Devices	9
1.4.3 SAS Expander Devices	9
1.4.4 SAS Ports	9
1.4.5 SAS Protocols	10
1.5 SAS Names and Addresses	11
1.5.1 SCSI Device Name	11
1.5.2 SCSI Port Name	12
1.5.3 SAS Addresses	12
1.5.4 SAS Port Identifier	13
1.5.5 PHY identifiers	13
1.6 SAS Structure and Layers	13
1.6.1 SAS Structure with Multiple Protocols	15
1.6.2 Information Encapsulation	15
1.6.3 Transmit Data Path and State Machines	15
1.7 SAS, the SCSI Bus, Fibre Channel and SATA	15
1.7.1 SAS = SCSI Bus + Fibre Channel + SATA	15
1.7.2 SAS, the SCSI Bus and Fibre Channel All Carry SCSI Commands	17
1.7.3 SAS Expanders Use Arbitration	19
1.7.4 Circuit Switching and Frame Switching	19
1.7.5 SAS is Serial	20
1.7.6 SAS Uses Embedded Clocking	21
1.7.7 SAS Does Not Have Messages	21
2. SAS Connections and Protocols	23
2.1 SAS Connections	23

2.2	Serial SCSI Protocol (SSP)	24
2.2.1	SSP Frame Acknowledgment	25
2.2.2	SSP Flow Control Characteristics	25
2.2.3	SSP Frame Transmission Example	25
2.2.4	SSP Task Management and Control-Type Command Examples	26
2.2.5	SSP Read Command Example	26
2.2.6	SSP Write Command Example	27
2.3	Serial Management Protocol (SMP)	27
2.3.1	SMP Protocol Example	27
2.4	SATA Tunneled Protocol (STP)	28
2.4.1	STP Frame Transmission Example	28
2.4.2	STP Characteristics	28
3.	SAS Configurations	31
3.1	Edge Expander Device Sets	32
3.1.1	Edge Expander Device Set Constraints	33
3.1.2	Edge Expander Routing Methods	33
3.1.3	Edge Expander Device Set Boundary	34
3.2	Fanout Expander	36
3.3	Wide Port Configurations	37
3.4	SAS JBOD With Integrated Expanders	39
4.	SAS Service Delivery Subsystem	41
4.1	SAS Physical Links	41
4.1.1	Differential Signaling	41
4.1.2	SAS PHYs	41
4.2	8b10b Encoding	42
4.3	Dwords and Primitives	42
4.3.1	Primitives and Dword Characteristics	43
4.3.2	SAS Primitives	43
4.4	Frame Transmission	44
4.4.1	Frame Protocol Example	44
4.5	Out-of-Band Signaling (OOB)	45
4.5.1	Device Determination Using OOB	45
4.5.2	Speed Negotiation	45
4.6	SAS Resets	46
4.6.1	SAS Reset Sequences	46
4.7	Device Identification	47
4.7.1	Attached Device Aware Capable	48
4.8	Connections	48
4.8.1	Connection Setup (OPEN)	49
4.8.2	Connection Characteristics	49
4.8.3	Connection Removal (CLOSE)	50
4.8.4	Wide Ports and Multiple Connections	50
4.9	Pathways	51
4.9.1	Pathway	53
4.9.2	Partial Pathway	53

4.9.3	Blocked Partial Pathways and Deadlock	53
4.10	Rate Matching	55
5.	SAS and SCSI Standards	57
5.1	SCSI Standards	59
5.2	Serial ATA Standards	60
5.3	Small Form Factor (SFF) Committee Documents	61
Section II. Serial SCSI Protocol		63
6.	SCSI Application Layer	65
6.1	SCSI Architecture Model	65
6.1.1	The SCSI Client-Server Model	66
6.2	SCSI Domain	67
6.2.1	SCSI Initiator Model	68
6.2.2	SCSI Target/Logical Unit Model	69
6.3	SCSI-3 Primary Commands	71
6.4	SCSI Addressing and Names	72
6.5	SCSI Data Transfer Model	72
6.6	SCSI Execute Command Model	73
6.6.1	Service Response	73
6.6.2	SCSI Nexus	74
6.6.3	SCSI Command Descriptor Block (CDB)	74
6.6.4	Task Attribute (Queue Type)	76
6.6.5	Data-In Buffer Size	77
6.6.6	Data-Out Buffer	77
6.6.7	Data-Out Buffer Size	77
6.6.8	Autosense Request	78
6.6.9	SCSI Status	78
6.6.10	Sense Data	78
6.6.11	Data-In Buffer	79
6.7	Task Management Functions	79
6.7.1	Task Management Function Requests	79
6.7.2	Task Management Function Responses	80
6.8	SCSI Application Layer Items Affected By SAS	80
6.8.1	SCSI Commands	80
6.8.2	SCSI Port Driver Impact	81
6.8.3	Disconnect-Reconnect Mode Page	82
6.8.4	Protocol-Specific Port Mode Page	84
6.8.5	Protocol-Specific Port Mode Sub-Page	85
6.8.6	SAS PHY Mode Descriptor	86
6.8.7	Protocol-Specific Logical Unit Mode Page	86
6.8.8	SCSI Log Parameters	87
6.8.9	Protocol-Specific Log Parameter	88
6.8.10	SAS PHY Log Descriptor	89
6.8.11	SCSI Vital Product Data (VPD)	90
6.8.12	SCSI Power Conditions	91

6.9	SCSI Application Layer Power Condition (SA_PC) State Machine	91
6.9.1	SA_PC_0:Powered_On State	93
6.9.2	SA_PC_1:Active State	93
6.9.3	SA_PC_2:Idle State	93
6.9.4	SA_PC_3:Standby State	94
6.9.5	SA_PC_4:Stopped State	94
6.9.6	10.2.9.2.7 SA_PC_5:Active_Wait State	95
6.9.7	SA_PC_6:Idle_Wait state	96
7.	SSP Transport Layer	97
7.1	SCSI Transport Protocol Services	97
7.1.1	Send SCSI Command	98
7.1.2	SCSI Command Received	99
7.1.3	Send Command Complete	100
7.1.4	Command Complete Received	101
7.1.5	Send Data-In Transport Protocol Service Request	102
7.1.6	Data-In Delivered	103
7.1.7	Receive Data-Out	104
7.1.8	Data-Out Received	105
7.1.9	Send Task Management Request	106
7.1.10	Task Management Request Received	107
7.1.11	Task Management Function Executed	107
7.1.12	Received Task Management Function-Executed	109
7.2	SSP Information Units	110
7.2.1	COMMAND Information Unit	111
7.2.2	TASK Information Unit	113
7.2.3	XFER_RDY Information Unit	114
7.2.4	DATA Information Unit	115
7.2.5	RESPONSE Information Unit	115
7.3	SSP Frame Format	117
7.3.1	SAS Address Hashing	121
7.4	SSP Frame Sequence Examples	121
7.4.1	SSP Task Management and Control-Type Command Example	122
7.4.2	SSP Read Command	122
7.4.3	SSP Write Command	123
7.4.4	SSP Write Command (First Burst Enabled)	123
8.	SSP Link Layer	125
8.1	SSP Link Layer Overview	125
8.1.1	Full Duplex Operation	125
8.1.2	SSP Frame Characteristics	125
8.2	SSP Flow Control	126
8.2.1	Credit Deadlock Avoidance	127
8.2.2	SSP Credit Blocked	127
8.3	SSP Frame Acknowledgement	127
8.3.1	ACK/NAK Balance	127
8.3.2	Interlocked and Non-Interlocked Frames	128

8.4	Closing an SSP Connection	129
8.4.1	DONE Primitives	129
8.5	SSP Link Layer Timers	129
8.6	SSP Done Timeout	129
9.	SSP Error Handling	131
9.1	SCSI Application Layer Error Handling	131
9.1.1	“Send SCSI Command” Errors	131
9.1.2	Second “Command Complete Received”	132
9.1.3	“Send Task Management” Errors	132
9.1.4	“Command Complete Received” Errors	133
9.1.5	“Receive Data-Out” Errors	134
9.2	SSP Transport Layer Handling of Link Layer Errors	134
9.2.1	COMMAND Frame Errors	135
9.2.2	XFER_RDY Frame Error With Transport Layer Retries	139
9.2.3	XFER_RDY Frame Without Transport Layer Retries	141
9.2.4	DATA Frame Errors With Transport Layer Retries	142
9.2.5	DATA Frame Errors Without Transport Layer Retries	145
9.2.6	RESPONSE Frame Errors	148
9.2.7	TASK Frame Errors	149
9.3	SSP Transport Layer Handling of Transport Layer Errors	150
9.3.1	SSP Initiator Port Handling of Transport Layer Errors	150
9.3.2	SSP Target Port Handling of Transport Layer Errors	151
9.4	SCSI Transport Protocol Event Notifications	153
10.	SSP Trace Examples	155
10.1	Test Unit Ready Command Trace	156
10.2	Read (10) Command	158
10.3	SSP Write (10) Command	160
11.	Reading SAS State Machine Diagrams	163
11.1	State Machine Conventions	163
11.1.1	Designators and State Names	164
11.1.2	Transitions	164
11.1.3	Messages	166
11.1.4	Requests, Indications, Confirmations, Responses, and Event Notifications	166
11.2	State Machine Example	166
12.	SSP Transport Layer (ST) State Machines	169
12.1	SSP Transport Layer (ST) Initiator State Machines	169
12.2	Initiator Frame Router (ST_IFR) State Machine	169
12.2.1	ST_IFR:Initiator_Frame_Router State	171
12.3	Initiator Transport Server (ST_ITS) State Machine	175
12.3.1	ST_ITS1:Initiator_Start State	176
12.3.2	ST_ITS2:Send_Frame State	176
12.3.3	ST_ITS3:Prepare_Command State	179
12.3.4	ST_ITS4:Prepare_Task State	180
12.3.5	ST_ITS5:Prepare_Data_Out State	181

12.3.6	ST_ITS6:Receive_Data_In State	182
12.3.7	ST_ITS7:Process_Data_In State	183
12.4	SSP Transport Target (ST_T) State Machines	183
12.5	ST Target Frame Router (ST_TFR) State Machine	183
12.6	ST_TTS (Target Transport Server) State Machine	190
12.6.1	ST_TTS1:Target_Start State	190
12.6.2	ST_TTS2:Target_Send_Frame State	191
12.6.3	ST_TTS3:Prepare_Data_In State	194
12.6.4	ST_TTS4:Prepare_Xfer_Rdy State	196
12.6.5	ST_TTS5:Receive_Data_Out State	197
12.6.6	ST_TTS6:Process_Data_Out State	198
12.6.7	ST_TTS7:Prepare_Response State	198
13.	SSP Link Layer State Machines	201
13.1	Transmitter and Receiver Messages	201
13.2	SSP_TIM (Transmit Interlocked Frame Monitor) State Machine	202
13.3	SSP_TCM (Transmit Frame Credit Monitor) State Machine	205
13.4	SSP_D (DONE Control) State Machine	205
13.5	SSP_TF (Transmit Frame Control) State Machine	206
13.5.1	SSP_TF1:Connected_Idle state	206
13.5.2	SSP_TF2:Tx_Wait State	207
13.5.3	SSP_TF3:Indicate_Frame_Tx State	208
13.5.4	SSP_TF4:Indicate_DONE_Tx State	208
13.6	SSP_RF (Receive Frame Control) State Machine	209
13.7	SSP_RCM (Receive Frame Credit Monitor) State Machine	209
13.8	SSP_RIM (Receive Interlocked Frame Monitor) State Machine	210
13.9	SSP_TC (Transmit Credit Control) State Machine	211
13.10	SSP_TAN (Transmit ACK/NAK Control) State Machine	211
Section III.	SMP Protocol	213
14.	Serial Management Protocol (SMP)	215
14.1	SMP Functions	217
14.2	SMP Report General Function	219
14.2.1	SMP Report General Response	219
14.3	SMP Discover Function	222
14.3.1	SMP Discover Response	222
14.4	SMP Report Route Information Function	227
14.4.1	SMP Report Route Information Response	227
14.5	SMP Configure Route Information Function	229
14.5.1	SMP Configure Route Information Response	230
14.6	SMP Report Manufacturer Information Function	231
14.6.1	SMP Report Manufacturer Information Response	231
14.7	SMP Report PHY Error Log Function	233
14.7.1	SMP Report PHY Error Log Response	233
14.8	SMP Report PHY SATA Function	235
14.8.1	Report PHY SATA Response	235

14.9	SMP PHY Control Function	237
14.9.1	PHY Control Response	239
14.10	SAS Management Protocol (SMP) Services	240
14.11	SMP Transport Layer and Frame Format	240
14.12	SMP Link Layer Operation	241
14.12.1	SMP Protocol Characteristics	241
14.12.2	SMP Protocol Example	242
14.12.3	CLOSE Connection	242
14.13	SMP Report General Trace	242
15.	Discovery Process	245
15.1	Attached Device Awareness	245
15.2	Discovery Process Initiation	246
15.2.1	Legal Attachments and Configuration Errors	246
15.3	Level-Order Traversal	247
15.4	Discovery Process Example	249
15.4.1	Discovery Process Diagram	251
15.4.2	Example Used For The Discovery Process	251
15.4.3	Discovery Process: Step 1	253
15.4.4	Discovery Process: Step 2	255
15.4.5	Discovery Process: Step 3	256
15.4.6	Discovery Process: Step 4	257
15.4.7	Discovery Process: Step 5	258
15.4.8	Discovery Process: Step 6	259
15.4.9	Discovery Process: Step 7	260
15.4.10	Discovery Process: Step 8	261
15.4.11	Discovery Process: Step 9	262
15.4.12	Discovery Process: Step 10	263
15.5	Route Table Optimization	264
15.6	Expander Route Index Order	266
15.7	Fanout Expander Discovery	268
16.	SMP Transport Layer (MT) State Machines	271
16.1	SMP Transport Initiator Port (MT_IP) State Machine	271
16.1.1	MT_IP1:Idle State	271
16.1.2	MT_IP2:Send State	272
16.1.3	MT_IP3:Receive state	273
16.2	SMP Transport Target Port (MT_TP) State Machine	273
16.2.1	MT_TP1:Idle State	273
16.2.2	MT_TP2:Respond State	274
17.	SMP Link Layer State Machines	275
17.1	SMP Initiator PHY (SMP_IP) State Machine	275
17.1.1	SMP Transmitter and Receiver	275
17.1.2	SMP_IP1:Idle state	276
17.1.3	SMP_IP2:Transmit_Frame State	277
17.1.4	SMP_IP3:Receive_Frame State	277
17.2	SMP Target PHY (SMP_TP) State Machine	277

17.2.1	SMP_TP1:Receive_Frame State	278
17.2.2	SMP_TP2:Transmit_Frame state	279
Section IV. SATA Tunneled Protocol	281	
18. STP Transport and Link Layers	283	
18.1	STP Application and Transport Layers	283
18.1.1	Initial Register - Device to Host FIS	283
18.1.2	TT (Transport Layer for STP Ports) State Machine	283
18.1.3	SATA Primitives	283
18.2	SATA Frame Characteristics	284
18.2.1	SATA Frame Transmission	285
18.3	SATA Flow Control	285
18.3.1	SATA Flow Control Budget	285
18.3.2	SATA Flow Control Example	286
18.4	STP Flow Control Rules	286
18.4.1	STP Flow Control Characteristics	287
18.4.2	Expander Flow Control Rules	288
18.4.3	SATA Outbound Flow Control	288
18.5	STP Connections	289
18.5.1	Initiator Port Opening an STP Connection	289
18.5.2	Target Port Opening an STP Connection	290
18.5.3	Closing an STP Connection	292
18.6	STP Affiliations	292
18.7	SATA Interface Power Management	292
18.7.1	SATA Power Management	293
18.8	Miscellaneous STP Link Layer Notes	293
18.9	SATA Port Multipliers and Port Selectors	293
18.9.1	SATA Port Multiplier	293
18.9.2	SATA Port Selector	294
18.10	STP Differences From SATA	296
18.10.1	STP Differences From Serial ATA (SATA)	296
18.10.2	STP Differences From Serial ATA-II	296
Section V. SAS Port Layer	297	
19. SAS Port Layer	299	
19.1	Port Layer Example Scenario	299
19.2	Port Layer Interfaces	301
20. SAS Port Layer (PL) State Machines	303	
20.1	Port Layer (PL) State Machines	303
20.2	PL_OC State Machine Overview	303
20.2.1	Port Level Overall Control (PL_OC) Timers	304
20.2.2	PL_OC1:Idle State	304
20.2.3	PL_OC2:Overall_Control State	305
20.2.4	PL_OC2:Overall_Control State (Establishing Connections)	306
20.2.5	PL_OC2:Overall_Control State (Connection Established)	309

20.2.6	PL_OC2:Overall_Control State (Unable To Establish A Connection)	310
20.2.7	PL_OC2:Overall_Control State (Connection Management)	310
20.2.8	PL_OC2:Overall_Control State (Frame Transmission)	312
20.2.9	PL_OC2:Overall_Control State (Frame Transmission Cancellations)	314
20.3	PL_PM State Machine Overview	314
20.3.1	PL_PM1:Idle State	314
20.3.2	PL_PM2:Req_Wait State	316
20.3.3	PL_PM2:Req_Wait (Establishing A Connection)	316
20.3.4	PL_PM2:Req_Wait (Connection Established)	316
20.3.5	PL_PM2:Req_Wait (Unable To Establish A Connection)	317
20.3.6	PL_PM2:Req_Wait (Connection Management)	318
20.3.7	PL_PM3:Connected State	318
20.3.8	PL_PM4:Wait_For_Close State	321
Section VI. SAS Link Layer		323
21. Primitives		325
21.1	What are Primitives?	325
21.1.1	Primitives Notation	325
21.1.2	Primitive Characteristics	326
21.1.3	Primitives Grouped by Connection Type	326
21.2	Primitive Sequences	327
21.2.1	Single Primitive Sequence	327
21.2.2	Repeated Primitive Sequence	328
21.2.3	Triple Primitive Sequences	328
21.2.4	Redundant Primitive Sequences	329
21.3	Primitive Descriptions	330
21.3.1	AIP (Arbitration in Progress)	330
21.3.2	Align	330
21.3.3	Break	331
21.3.4	Broadcast	331
21.3.5	Close Primitive	332
21.3.6	SOAF and EOAF Primitives	332
21.3.7	Error	332
21.3.8	Hard_Reset	333
21.3.9	NOTIFY	333
21.3.10	Open_Accept and Open_Reject	334
21.3.11	Open_Reject Retry Primitives	334
21.3.12	ACK	336
21.3.13	Credit_Blocked	336
21.3.14	DONE	337
21.3.15	NAK	337
21.3.16	RRDY	337
21.3.17	SOF and EOF	338
21.3.18	STP Primitives	338
21.4	Primitive Usage Table	339
21.5	Primitive Encoding	342

22. Clock Skew and Scrambling	345
22.1 ALIGN/NOTIFY Insertion Requirements	346
22.2 Elasticity Buffer	347
22.2.1 Clock Skew Management Examples	348
22.3 Idle Physical Links	348
22.4 Scrambling Overview	349
22.4.1 Scrambling Data Dword Types	349
22.5 Transmit and Receive Path Bit Ordering	350
22.5.1 Transmit Path Bit Ordering	350
22.5.2 Receive Path Bit Ordering	352
22.5.3 SAS STP Transmit Bit Order	353
22.5.4 SAS STP Receive Bit Order	354
22.6 Cyclic Redundancy Check (CRC)	355
23. Address Frames	357
23.1 Address Frame Characteristics	357
23.1.1 Address Frame Format	357
23.2 IDENTIFY Address Frame	357
23.3 OPEN Address Frame	359
24. Identification and Hard Reset	363
24.1 Identification and Hard Reset Sequence Overview	363
24.2 Identification and Hard Reset Sequences	363
24.2.1 SAS Hard Reset Sequence	364
24.2.2 SAS Initiator Device Rules	365
24.2.3 Fanout Expander Device Rules	365
24.2.4 Edge Expander Device Rules	366
25. Connections	367
25.1 Connection Setup	368
25.1.1 Arbitration Wait Time (AWT)	370
25.1.2 Open Timeout Timer	371
25.1.3 Responses To An OPEN Address Frame	372
25.1.4 Connection Response: Arbitration In Progress (AIP)	372
25.1.5 Connection Response: OPEN_ACCEPT	373
25.1.6 Connection Response: OPEN_REJECT	373
25.1.7 OPEN_REJECT Priorities	374
25.1.8 Connection Response: OPEN Address Frame	375
25.1.9 Connection Response: BREAK	377
25.1.10 Connection Request Timeout Example	377
25.2 Processing During an Open Connection	377
25.3 Closing a Connection	378
25.3.1 Normal Close Protocol	378
25.3.2 CLOSE Protocol Example	379
25.3.3 Aborting a Connection with BREAK	379
25.3.4 Using BREAK to Abort a Connection: Case 1	380
25.3.5 Using BREAK to Abort a Connection: Case 2	380
25.3.6 Using BREAK to Abort a Connection: Case 3	381

26. Expanders	383
26.1 Expander Structure	383
26.1.1 Expander Ports and PHYs	384
26.1.2 Expander Connection Manager (ECM)	384
26.1.3 Expander Connection Router (ECR)	384
26.1.4 Broadcast Primitive Processor (BPP)	385
26.1.5 SMP Target Port	385
26.1.6 Embedded Initiator/Target Ports	385
26.1.7 SAS to SATA Bridges	386
26.2 Expander Addressing	386
26.3 Expander Routing	387
26.3.1 ECM Routing Methods	387
26.3.2 Routing Rules	388
26.3.3 Routing Precedence	388
26.3.4 Expander Route Table	388
26.4 Expander Types	390
26.4.1 Edge Expander	390
26.4.2 Edge Expander Device Sets	390
26.4.3 Fanout Expander	391
26.5 Expander IDENTIFY Address Frame	391
26.6 Expander Internal Interface Model	392
26.7 Expander Connection Manager (ECM) Arbitration	394
26.7.1 PHY Status to the Expander Connection Manager (ECM)	395
26.7.2 Arbitration Status From the ECM	395
26.7.3 Arbitration Fairness	398
26.7.4 Retry Priority Status	398
26.8 Contention For Path Resources and Deadlock Recovery	398
26.8.1 Waiting on Connection	399
26.9 Deadlocks and Pathway Recovery	400
26.9.1 Deadlock Recovery Within a Single Expander	401
26.9.2 Circular Deadlocks	402
26.9.3 Pathway Recovery	402
26.10 Expander Connection Router (ECR)	404
26.10.1 Invalid Dword Processing	405
26.11 Broadcast Primitive Processor (BPP)	405
26.12 Example Expander Implementation	406
26.13 Expander Scenario Examples	407
26.13.1 Connection Request: OPEN_ACCEPT	408
26.13.2 Connection Request: OPEN_REJECT By End Device	409
26.13.3 Connection Request: OPEN_REJECT By Expander	410
26.13.4 Connection Request: Arbitration Lost	411
26.13.5 Connection Request: Backoff and Retry	412
26.13.6 Connection Request: Backoff and Reverse Path	413
26.13.7 Connection Close: Non-Overlapping CLOSE Primitives	414
26.13.8 Connection Close: Overlapping CLOSE Primitives	415

26.13.9	STP Connection: Originated by STP Initiator Port	416
26.13.10	STP Connection: Originated by STP Target Port	417
27.	SAS Link Layer (SL) State Machines	419
27.0.1	SL Transmitter and Receiver	419
27.1	Receive Address Frame (SL_RA) State Machine	421
27.2	Connection Control (SL_CC) State Machine	422
27.2.1	SL_CC State Machine Messages	422
27.2.2	SL_CC0:Idle state	423
27.2.3	SL_CC1:ArbSel State	423
27.2.4	SL_CC2:Selected State	425
27.2.5	SL_CC3:Connected State	427
27.2.6	SL_CC4:DisconnectWait State	427
27.2.7	SL_CC5:BreakWait State	428
27.2.8	SL_CC6:Break State	428
27.2.9	SL_CC7:CloseSTP state	428
28.	Identification and Hard Reset State Machines	429
28.1	SL_IR_TIR State Machine	431
28.1.1	SL_IR_TIR1:Idle State	431
28.1.2	SL_IR_TIR2:Transmit_Identify State	431
28.1.3	SL_IR_TIR3:Transmit_Hard_Reset State	431
28.1.4	SL_IR_TIR4:Completed State	432
28.2	SL_IR_RIF State Machine Overview	432
28.2.1	SL_IR_RIF1:Idle State	432
28.2.2	SL_IR_RIF2:Receive_Identify_Frame State	432
28.2.3	SL_IR_RIF3:Completed State	433
28.3	SL_IR_IRC State Machine Overview	433
28.3.1	SL_IR_IRC1:Idle State	433
28.3.2	SL_IR_IRC2:Wait State	433
28.3.3	SL_IR_IRC3:Completed State	434
29.	Expander Link Layer (XL) State Machines	435
29.1	Expander Link Layer (XL) State Machine	435
29.1.1	XL State Machine Messages	436
29.1.2	XL Transmitter and Receiver Message	436
29.1.3	XL0:Idle State	437
29.1.4	XL1:Request_Path State	437
29.1.5	XL2:Request_Open state	439
29.1.6	XL3:Open_Confirm_Wait state	440
29.1.7	XL4:Open_Reject State	441
29.1.8	XL5:Forward_Open state	441
29.1.9	XL6:Open_Response_Wait state	442
29.1.10	XL7:Connected state	444
29.1.11	XL8:Close_Wait State	444
29.1.12	XL9:Break State	445
29.1.13	XL10:Break_Wait State	445

Section VII. SAS PHY Layer	449
30. Dwords, Encoding and Serialization	451
30.1 SAS Dword	451
30.1.1 SAS and SATA Byte Ordering	451
30.2 Encoding	452
30.2.1 8b10b Description	452
30.2.2 Why Encode the Data?	453
30.2.3 Running Disparity	453
30.2.4 Data Characters and Special Characters	454
30.2.5 8b10b Bit and Byte Notation	454
30.2.6 Encoding/Decoding Process	455
30.2.7 5b/6b Subblock Encoding	455
30.2.8 3b/4b Subblock Encoding	457
30.2.9 8b10b Data Byte Encoding	457
30.2.10 8b10b Special Character Encoding	463
30.2.11 Comma Pattern	463
30.2.12 Bit and Byte Transmission Order	464
30.3 8b10b Error Detection	464
30.3.1 Code Violation Errors	465
30.3.2 Disparity Errors	465
30.3.3 Error Detection	465
30.4 8b10b Summary	466
30.5 Transmitter Operation	467
30.6 SAS Bit Transmission Order	468
30.7 SAS Bit Reception Order	469
31. Out-of-Band Signaling	471
31.1 Out-of-Band (OOB) Signals	471
31.1.1 OOB Signal Level Requirements	471
31.1.2 OOB Signal Timing Requirements	472
31.1.3 Out-of-Band Signal Detection	472
31.2 Out-of-Band Detection Examples	473
31.2.1 ALIGN Requirements	475
31.2.2 Expander Devices	475
31.3 OOB Signal Detector	475
32. PHY Reset Sequences and Speed Negotiation	477
32.1 PHY Reset Sequences Overview	477
32.2 SAS to SAS PHY Reset	477
32.3 SAS Speed Negotiation	479
32.3.1 SAS Speed Negotiation Sequence	479
32.4 Hot Plug Detection	481
32.5 SATA PHY Reset and Speed Negotiation	483
32.5.1 SATA Speed Negotiation Timings	483
32.5.2 SAS to SATA PHY Reset	484

33. PHY Layer State Machines	487
33.1 SP State Machine	487
33.1.1 SP (PHY Layer) State Machine Characteristics	487
33.1.2 SP Transmitter And Receiver	488
33.2 SP (PHY Layer) State Machine	489
33.2.1 SP0:OOB_COMINIT State	489
33.2.2 SP1:OOB_AwaitCOMX State	489
33.2.3 SP2:OOB_NoCOMSASTimeout State	491
33.2.4 SP3:OOB_AwaitCOMINIT_Sent State	491
33.2.5 SP4:OOB_COMSAS State	491
33.2.6 SP5:OOB_AwaitCOMSAS_Sent State	492
33.2.7 SP6:OOB_AwaitNoCOMSAS State	492
33.2.8 SP7:OOB_AwaitCOMSAS State	492
33.3 SP Speed Negotiation States	493
33.3.1 SP8:SAS_Start State	493
33.3.2 SP9:SAS_RateNotSupported State	493
33.3.3 SP10:SAS_AwaitALIGN State	493
33.3.4 SP11:SAS_AwaitALIGN1 State	495
33.3.5 SP13:SAS_Pass State	496
33.3.6 SP14:SAS_Fail State	496
33.3.7 SP15:SAS_PHY_Ready State	497
33.4 SP State Machine SATA States	497
33.4.1 SP16:SATA_COMWAKE State	497
33.4.2 SP17:SATA_AwaitCOMWAKE State	499
33.4.3 SP18:SATA_AwaitNoCOMWAKE State	499
33.4.4 SP19:SATA_AwaitALIGN State	499
33.4.5 SP20:SATA_AdjustSpeed State	499
33.4.6 SP21:SATA_TransmitALIGN State	500
33.4.7 SP22:SATA_PHY_Ready State	500
33.4.8 SP23:SATA_PM_Partial State	500
33.4.9 SP24:SATA_PM_Slumber State	501
33.5 SP SATA Port Selector State	501
33.6 SP_DWS State Machine	502
33.6.1 SP_DWS Receiver	502
33.6.2 SP_DWS0:AcquireSync State	504
33.6.3 SP_DWS1:Valid1 State	504
33.6.4 SP_DWS2:Valid2 State	504
33.6.5 SP_DWS3:SyncAcquired State	505
33.6.6 SP_DWS4:Lost1 State	505
33.6.7 SP_DWS5:Lost1Recovered State	505
33.6.8 SP_DWS6:Lost2 State	505
33.6.9 SP_DWS7:Lost2Recovered State	506
33.6.10 SP_DWS8:Lost3 State	506
33.6.11 SP_DWS9:Lost3Recovered State	506

Section VIII. SAS Physical Layer	507
34. Cables and Connectors	509
34.1 SATA Cables and Connectors	509
34.1.1 SATA Connector Placement	511
34.1.2 SATA Device Connector Pinout	512
34.1.3 SATA Physical Cabling Example	513
34.1.4 SATA Backplane Cabling Example	514
34.2 SAS Cables and Connectors	515
34.2.1 Single-Ported SAS Internal Cabled Environment	515
34.2.2 Dual-Ported Internal Cabled Environment	516
34.2.3 SAS Plug (Device) Connector	516
34.2.4 SAS Backplane Connector	517
34.2.5 SAS Internal Cables	518
34.2.6 SAS - HBA, Multi-Lane Cabled and Backplane Example	519
34.2.7 SAS Dual/Redundant HBAs and Backplane Example	520
34.2.8 SAS External Cable Connector	521
34.3 Hot-Plug Considerations	522
34.3.1 Backplane Power Mating Sequence	522
34.4 SAS/SATA Cables and Supported Links	523
35. Transmitter and Receiver	525
35.1 SAS Physical Link	525
35.2 Differential Signaling	526
35.2.1 Differential Signaling Levels	527
35.2.2 D.C. Idle	527
35.2.3 A.C. and D.C. Coupling	528
35.3 Timing Requirements and Clocking	528
35.3.1 Clock and Data Recovery	528
35.3.2 Jitter	529
35.4 Bit Error Rate (BER) Requirements	529
35.5 The Eye Diagram or Mask	530
35.6 Cable and Connector Losses	531
35.6.1 Cable and Connector Losses	531
35.7 Countering Interconnect Losses	532
35.7.1 Transmitter Pre-Emphasis	532
35.7.2 Receiver Equalization	533
35.8 SAS vs. SATA Considerations	534
35.8.1 SATA Devices and Spread-Spectrum Clocking (SSC)	534
35.8.2 SAS and SATA Signaling Levels	535
35.9 SAS Extended Distance Considerations	535
35.9.1 Physical Link Considerations	535
35.9.2 SAS Protocol Considerations	536
35.10 SAS Transmitter and Receiver Specifications	536
35.10.1 TxRx Compliance Points	536
35.10.2 General Interface Characteristics	537
35.10.3 Signal Characteristics at IT, CT, XT	538

35.10.4 Signal Characteristics at IR, CR, and XR	538
35.10.5 Maximum Allowable Jitter at IR, CR, XR	540
35.10.6 Receiver Jitter Tolerance	541
35.10.7 Impedance Specifications	542
Section IX. Reference Material	543
A. State Machine Messages	543
B. SCSI Sense Data	547
B.1 Sense Data Format	548
B.2 Sense Key Descriptions	553
B.3 Numerical List of ASC and ASCQ Assignments	554
C. SCSI Operation Codes	565
D. Glossary	571
D.1 Symbols and Abbreviations	579
Index	583