
About This Book

The MindShare Architecture Series	1
Cautionary Note	2
Specifications This Book is Based On	3
Organization of This Book	3
Part One: Overview of USB 2.0.....	3
Part Two: Low- & Full-Speed Device Operation	4
Part III: High-Speed Device Operation.....	5
Part IV: USB 2.0 Hub Operation with LS/FS/HS Devices	5
Part VI: USB Software Overview.....	6
Appendices	7
Who Should Read this Book	7
Prerequisite Knowledge	7
Documentation Conventions.....	8
Hexadecimal Notation	8
Binary Notation.....	8
Decimal Notation.....	8
Bits Versus Byte Notation.....	8
Identification of Bit Fields (logical groups of bits or signals)	9
Visit Our Web Page	9
We Want Your Feedback.....	9

Part One

Overview of USB 2.0

Chapter 1: Design Goals of USB

Shortcomings of the Original PC I/O Paradigm	13
Limited System Resources	14
Interrupts	15
I/O Addresses.....	16
Non-shareable Interfaces	16
End User Concerns	16
Cable Crazy	17
Installation and Configuration of Expansion Cards.....	17
No Hot Attachment of Peripherals	17
Cost	18
The USB Paradigm.....	18
Enhanced System Performance.....	19
Hot Plug and Play Support	20

Contents

Expandability.....	20
Legacy Hardware/Software Support	20
Low Cost	21
Summary of Key USB Features.....	23
How to Get the USB Specifications.....	24

Chapter 2: The Big Picture

Overview.....	25
USB 1.x Systems and Devices.....	28
Low-Speed and Full-Speed Devices.....	28
How Transactions Are Generated.....	30
What the Descriptors Contain.....	30
How the Transfer Descriptors Are Fetched	30
Frame Generation	33
Sharing the Bus.....	34
Bandwidth Consideration Summary	34
2.0 Systems and Devices	37
Low-Speed and Full-Speed Devices in a 2.0 System	38
Example 2.0 Host Controller Support for LS/FS Devices	40
High-Speed Devices in a 2.0 System	41
High-Speed Devices Attached to 1.x Ports	41
High-Speed Transactions and Microframe Generation	42
High-Speed Bandwidth Summary	42
The Players	44
USB Client Drivers.....	45
USB Bus Driver.....	46
USB Host Controller Driver	46
USB Host Controller/Root Hub	47
The Host Controller.....	47
The Root Hub	48
USB Hubs	49
Hub Controller.....	51
Hub Repeater.....	52
Hub's Role in Configuration.....	53
USB Devices	53
High-Speed Devices	53
Full-Speed Devices	53
Low-Speed Devices	53
USB Communications Model	54
Communications Flow	54
Transfers, IRPs, Frames, and Packets.....	55
Transfers.....	55

The USB Driver, IRPs, and Frames	57
The Host Controller Driver and Transactions	59
The Host Controller and Packets.....	60
Device Framework (how devices present themselves to software).....	60
Device Descriptors.....	60
Device Framework.....	63
USB Bus Interface Layer	63
USB Device Layer	64
Function Layer	65
USB Peripheral Connection	66
Full-Speed Hubs.....	66
High-Speed Hubs.....	67
High-Speed Devices	67
Low- and Full-Speed Devices	67
Topology	67

Chapter 3: Cables and Connectors

The Connectors.....	69
Series A Connectors.....	71
Series B Connectors.....	71
Cables	71
Low-Speed Cables.....	72
Full- and High-Speed Cables	73
Cable Power	74
Electrical and Mechanical Specifications.....	74

Chapter 4: USB Cable Power Distribution

USB Power	75
Hubs.....	76
Current Budget.....	76
Over-Current Protection	78
Voltage Drop Budget.....	78
Power Switching	79
Bus-Powered Hubs	80
Power During Hub Configuration	80
Bus-Powered Hub Attached to 500ma Port	80
Bus-Powered Hub Attached to 100ma Port	80
Bus-Powered Hub Attached to Port with >100ma but <500ma	81
Current Limiting	81
Bus-Powered Devices	82
Low-Power Devices.....	82

Contents

High-Power Devices	83
Power During Configuration	83
Insufficient Port Power	84
Self-Powered Hubs	86
Power During Configuration	87
Locally Powered Bus Interface	87
Hybrid Powered Device	87
Current Limiting	88
Self-Powered Devices.....	89
Power During Configuration	89
Locally Powered Bus Interface	89
Hybrid Powered Device	89

Part Two Low- & Full-Speed Device Operation

Chapter 5: LS/FS Signaling Environment

Overview.....	93
Detecting Device Attachment and Speed Detect.....	94
Full-Speed Device Connect.....	98
Low-Speed Device Connect.....	100
Detecting Device Disconnect.....	101
Bus Idle	102
Device RESET	103
Differential Signaling	104
Differential Drivers.....	106
Full-Speed Drivers	106
Low-Speed Drivers.....	108
Hub Driver Characteristics.....	109
Differential Receivers	109
Start of Packet (SOP).....	109
End of Packet (EOP)	110
Single-Ended Receivers.....	110
NRZI Encoding.....	111
Bit Stuffing	112
Summary of USB Signaling States	113

Chapter 6: LS/FS Transfer Types & Scheduling

Overview.....	117
Client Initiates Transfer.....	118
Communications Pipes	119

Communication Initiated by I/O Request Packets	120
Frame-Based Transfers	121
Transfer Types	122
Isochronous Transfers	123
Direction of Transfers	123
Service Period	123
Bandwidth Allocation	123
Error Recovery	124
Establishing Synchronous Connections	125
The Problem with Isochronous Transfers	125
The Feedback/Feed Forwarding Solution	128
Synchronization Types	128
Source/Sink Combinations and Synchronization Methods	129
Asynchronous Source and Asynchronous Sink	130
Asynchronous Source and Synchronous Sink	130
Asynchronous Source and Adaptive Sink	130
Synchronous Source and Asynchronous Sink	130
Synchronous Source and Synchronous Sink	130
Synchronous Source and Adaptive Sink	130
Adaptive Source and Asynchronous Sink	131
Adaptive Source and Synchronous Sink	131
Adaptive Source and Adaptive Sink	131
How Endpoints Report Their Synchronization Capabilities	131
Feedback Data	131
Association Between Data Endpoint and Feedback Endpoint	134
Interrupt Transfers	134
Service Period	134
Bus Bandwidth Allocation	135
Error Recovery	135
Control Transfers	136
Bus Bandwidth Allocation	137
Error Recovery	137
Bulk Transfers	137
Bus Bandwidth Allocation	137
Error Recovery	139

Chapter 7: Packets & Transactions

Overview	141
Packets — The Basic Building Blocks of USB Transactions	143
Synchronization Sequence	144
Packet Identifier	145
Packet-Specific Information	146

Contents

Cyclic Redundancy Checking (CRC)	146
End of Packet (EOP)	147
Token Packets	147
SOF Packet	148
IN Packet	149
OUT Packet	150
SETUP Packet	151
Data Packets — DATA0 and Data1	152
Handshake Packets	153
Preamble Packet	154
Transactions	156
IN Transactions	156
IN Transaction Without Errors	157
IN Transaction with Errors.....	157
IN Transaction with No Interrupt Pending/Target Busy	158
IN Transaction with Target Stalled	159
IN Transaction During Isochronous Transfer	159
OUT Transactions	160
OUT Transaction Without Data Packet Errors.....	160
OUT Transaction with Errors.....	161
OUT Transaction — Target Unable to Accept Data	161
OUT Transaction With Target Stalled	162
OUT Transaction During Isochronous Transfer	162
Setup Transactions/Control Transfers	163
Two Stage Control Transfer	164
Three Stage Control Transfer with IN Data Stage	165
Three Stage Control Transfer with OUT Data Stage	166
Control Transfers With Errors	166

Chapter 8: Error Recovery

Overview	167
Packet Errors	168
PID Checks.....	168
CRC Errors.....	169
Bit Stuff Errors.....	170
Packet-Related Error Handling.....	171
Token Packet Errors	171
IN Packet Errors.....	171
OUT or SETUP Packet Errors	171
Data Packet Errors.....	171
During OUT or SETUP Transactions.....	171
During IN Transactions	171

Handshake Packet Errors	172
During OUT Transactions	172
During IN Transactions	172
Bus Time-Out	172
False EOPs	174
False EOP During Host Transmission	174
False EOP During Target Transmission	174
Data Toggle Errors	175
Data Toggle Procedure Without Errors	175
Data Toggle during OUT Transactions	175
Data Toggle During IN Transactions.....	178
Data Toggle Procedure with Data Packet Errors	179
Data Toggle and Data Packet Errors — OUT Transactions.....	180
Data Toggle and Data Packet Errors — IN Transactions.....	182
Data Toggle Procedure With Handshake Packet Errors	183
Data Toggle and Handshake Errors — OUT Transactions	184
.....	186
Data Toggle With Handshake Packet Error — IN Transaction	186
Special Case: Data Toggle During Control Transfer	188
Babbling Devices	189
Loss of Activity (LOA)	189
Babble/LOA Detection and Recovery	189
Frame Timer.....	189
Host to Hub Skew	190
Hub Repeater State Machine.....	191
Isochronous Transfers (Delivery Not Guaranteed)	193
Interrupt Transfer Error Recovery	193
Bulk Transfer Error Recovery	193
Control Transfer Error Recovery.....	193

Chapter 9: USB Power Conservation

Power Conservation — Suspend.....	195
Device Response to Suspend.....	196
Hub Response to Suspend.....	196
Global Suspend	197
Initiating Global Suspend	197
Resume from Global Suspend.....	197
Resume Initiated by Host	198
Remote Wakeup from Device.....	199
Remote Wakeup via Hub Port Event.....	199
Selective Suspend	201
Initiating Selective Suspend	201

Contents

Resume from Selective Suspend	201
Host Initiated Selective Resume	201
Selective Wakeup from Device	202
Selective Suspend When Hub is Suspended.....	204
Device Signals Resume	204
Port Receives Connect or Disconnect	206
Selective Suspend Followed by Global Suspend.....	206
Resume via Reset	206
Hub Frame Timer After Wakeup	208

Part Three High Speed Device Operation

Chapter 10: Overview of HS Device Operation

Overview.....	213
New High-Speed Device Features	214
1.x USB Device Support.....	214
The 2.0 Host Controller.....	216

Chapter 11: The High-Speed Signaling Environment

Overview.....	217
Detecting High-Speed Device Attachment	219
Initial Device Detection.....	221
Device Reset and the Chirp Sequence.....	221
High-Speed Interfaces Idled.....	223
High-Speed Differential Signaling	224
Impedance Matching.....	224
High-Speed Driver Characteristics.....	226
High-Speed Idle	227
High-Speed Differential Receivers	227
High-Speed Driver/Receiver Compliance Testing.....	228
Activating Test Mode.....	229
The Test Setup.....	230
Eye Pattern Tests.....	231
Transmit Eye Pattern Tests.....	232
Receiver Eye Pattern Tests	233
High-Speed Start of Packet & Synchronization Sequence	234
High-Speed End of Packet (EOP).....	236
Detection of High-Speed Device Removal	236
High-Speed RESET and Suspend.....	239
Signaling RESET.....	239

Signaling Suspend	239
Differentiating Between RESET and Suspend	240

Chapter 12: HS Transfers, Transactions, & Scheduling

Overview	242
High-Speed Transaction Scheduling	242
Microframes	243
Theoretical HS Bandwidth	243
Periodic Transfers	244
High-Speed Isochronous Transfers	244
Maximum Packet Size	244
Isochronous Bandwidth/Performance	244
Isochronous Transaction Errors	247
High-Speed Interrupt Transfers	247
Maximum Packet Size	247
Interrupt Bandwidth	247
Interrupt Transaction Errors	249
High-Bandwidth Transactions	249
Detecting High-Bandwidth Endpoints and Packet Size	250
Isochronous High-Bandwidth Scheduling and Protocol	251
High-Bandwidth Isochronous IN Transactions	252
High-Bandwidth Isochronous OUT Transactions	252
High Bandwidth Interrupt Transactions	253
High Bandwidth Throughput	254
Non-Periodic Transfers	254
High-Speed Bulk Transfers	255
Maximum Packet Size	255
Bulk Bandwidth	255
Bulk Transactions Errors	257
High-Speed Control Transfers	257
High-Speed Control Bandwidth	257
Ping Transactions	260
The Problem	260
The Solution	260
The Ping Protocol	261
PING Packet Handshake Responses	263

Contents

Chapter 13: HS Error Detection and Handling

Overview.....	265
High-Speed Bus Time-out.....	266
False EOP.....	267
HS Babbling Device Detection.....	268

Chapter 14: HS Suspend and Resume

Overview.....	271
Entering Device Suspend.....	272
Device Resume.....	273

Part Four

USB 2.0 Hub Operation with LS/FS/HS Devices

Chapter 15: HS Hub Overview

Overview.....	277
USB 2.0 Hub Attached to High-Speed Port.....	278
High-Speed Transactions.....	280
Low- and Full-Speed Transactions.....	280
USB 2.0 Hub Attached to Full-Speed Port.....	281

Chapter 16: 2.0 Hubs During HS Transactions

Overview.....	283
High-Speed Hub Repeater.....	284
Receiver Squelch.....	285
Re-clocking the Packet.....	285
Port Selector State Machine.....	285
Elasticity Buffer.....	286
The Repeater State Machine.....	286

Chapter 17: 2.0 Hubs During LS/FS Transactions

Overview.....	289
The Structure of Split Transactions.....	290
Isochronous Split Transaction Examples.....	291
Example Split Isochronous OUT Transaction.....	291
Example Split Isochronous IN Transaction.....	292
Example Split Transactions with Data Verification.....	293
Split OUT Sequence.....	294

Split IN Sequence	295
The Split Token Packet	296
The Transaction Translator	297
The Major Elements of the Transaction Translator	297
High-Speed Handler	298
Periodic Transfer Start-Split Buffer	299
Periodic Complete-Split Buffer	299
Bulk/Control Buffers	299
Low-Speed/Full-Speed Handler	299
Split Transaction Scheduling	300
Split Transaction Scheduling Example	300
SOF Packets	300
Host Delivers Isochronous Start Split	301
Host Delivers Interrupt Start Split	302
Full- and Low-Speed Transactions Begin	303
Host Issues Complete-Split to Fetch Isochronous IN Data	304
Host Fetches Interrupt OUT Completion Status	305
Host Continues to Fetch Isochronous IN Data	306
Transaction End	307
High-Speed Scheduling Can Include Other Transactions	308
Single versus Multiple Transaction Translators	309
Periodic Split Transactions	310
Periodic Split Transaction Pipeline	311
High Speed Handler Receives Start Split	311
Start-Split Buffer	312
Low-Speed/Full-Speed Handler	312
Complete-Split Buffer	312
Isochronous OUT Split Transaction Sequence	313
Isochronous OUT Start Split	313
Start-Split Transaction Received with No Errors	315
Start-Split Transaction with Errors	315
Handling CRC16 During Split Isochronous OUT Transactions	315
Isochronous IN Split Transaction Sequence	316
Isochronous IN Start Split	316
Isochronous IN Complete Split	317
Complete Split Packet Error	317
Complete Split with MDATA	318
Complete Split with DATA0	318
Complete Split with NYET	318
Complete Split with ERR	319
Handling CRC16 During Split Isochronous IN Transactions	319
Interrupt Split OUT Transaction Sequence	319

Contents

Interrupt OUT Start Split Sequence	319
Interrupt OUT Complete Split Sequence	320
Complete Split Packet Error.....	321
Complete Split with ACK.....	322
Complete Split with NYET.....	322
Complete Split with NAK	322
Complete Split with STALL.....	322
Complete Split with ERR.....	322
Interrupt IN Split Transaction Sequence	322
Interrupt IN Start Split Sequence	323
Interrupt IN Complete Split Sequence	323
Complete Split Packet Error.....	324
Complete Split with MDATA	324
Complete Split with DATA0/1	325
Complete Split with NYET.....	325
Complete Split with NAK	325
Complete Split with STALL.....	326
Complete Split with ERR.....	326
Handling CRC16 During Split Interrupt IN Transactions.....	326
Non Periodic Split Transactions	327
Non-Periodic Split Transaction Pipeline	327
High Speed Handler.....	328
Non-periodic Buffers.....	328
Low-/Full-Speed Handler.....	328
Bulk/Control Split OUT Transaction Sequence	328
Bulk/Control OUT Start Split Sequence	329
Start Split with Packet Error.....	329
Start Split with ACK.....	330
Start Split with NAK	330
Bulk/Control OUT Complete Split Sequence	330
Complete Split Packet Error.....	331
Complete Split with ACK.....	331
Complete Split with NYET.....	332
Complete Split with NAK	332
Complete Split with STALL.....	332
Bulk/Control Split IN Transaction Sequence	332
Bulk/Control IN Start Split Sequence	332
Start Split with Packet Error.....	333
Start Split with ACK.....	334
Start Split with NAK	334
Bulk/Control IN Complete Split Sequence	334
Complete Split Packet Error.....	335

Complete Split with NYET.....	336
Complete Split with NAK.....	336
Complete Split with STALL.....	336

Part Five USB Device Configuration

Chapter 18: Configuration Process

Overview.....	339
The Configuration Software Elements.....	341
USB Host Controller Driver.....	342
Configuration Software.....	342
Default Control Pipe.....	342
Resource Management.....	343
Device Client Software.....	343
Root Hub Configuration.....	343
Each Device Is Isolated for Configuration.....	344
Reset Forces Device to Default Address (zero).....	345
Host Assigns a Unique Device Address.....	345
Host Software Verifies Configuration.....	345
Power Requirements.....	345
Bus Bandwidth.....	346
Configuration Value Is Assigned.....	346
Client Software Is Notified.....	346

Chapter 19: USB Device Configuration

Overview.....	347
Summary of Configuration Process.....	348
How Software Detects Device Attachment & Speed.....	348
Polling the Status Change Endpoint.....	349
Getting Port Status.....	350
Resetting the Port.....	352
Reading and Interpreting the USB Descriptors.....	353
The Standard Descriptors.....	353
How Software Accesses the Descriptors.....	354
Device Descriptor.....	355
Class Code Field.....	358
Maximum Packet Size Zero.....	359
Manufacturer, Product, Serial Number.....	359
Number of Configurations.....	359
Device Qualifier Descriptor.....	360

Contents

Configuration Descriptors	361
Number of Interfaces.....	361
Configuration Value	361
Attributes and Maximum Power	361
Other Speed Configuration Descriptor	363
Interface Descriptors.....	364
Interface Number and Alternate Setting	364
Number of Endpoints	365
Interface Class and Subclass.....	366
Protocol	366
Endpoint Descriptors	367
Device States	371
Attached State.....	371
Powered State	372
Default State.....	372
Addressed State.....	372
Configured State	372
Suspend State.....	373
Client Software Configuration.....	374

Chapter 20: Hub Configuration

Configuring the Hub	376
The Default Pipe.....	376
The Status Change Pipe	376
Reading the Hub's Descriptors	377
1.x Hub Descriptors	378
Hub's Standard Device Descriptor.....	379
Hub Configuration Descriptor.....	380
Number of Interfaces.....	381
Configuration Value	381
Bus- or Self-Powered Hub	381
Maximum Bus Power Consumed	381
Hub Interface Descriptor	383
Status Endpoint Descriptor	384
Status Change Endpoint Address/Transfer Direction.....	385
Transfer Type	385
Maximum Data Packet Size.....	385
Polling Interval.....	385
Hub Class Descriptor	387
Power Switching Mode Implemented.....	387
Compound Device or Hub Only	390
Over-Current Protection Mode.....	390

Power On to Power Good Delay	390
Maximum Bus Current for Hub Controller	390
Device Removable/Non-removable	390
Port Power Mask.....	391
High-Speed Capable Hub Descriptors	391
Descriptors When Hub Is Operating at Full Speed	391
The 2.0 Hub's Class-Specific Descriptor	394
Powering the Hub	397
Checking Hub Status.....	397
Detecting Hub Status Changes	397
Reading the Hub Status Field.....	398
Reading Port Status	399
Enabling the Device	399
Summary of Hub Port States	399

Chapter 21: Device Classes

Overview.....	403
Device Classes	406
Audio Device Class.....	407
Standard Audio Interface Requirements.....	408
Synchronization Types.....	409
Audio Class-Specific Descriptors	409
Audio Class-Specific Requests.....	410
Communications Device Class.....	410
Communications Device Interfaces.....	411
Communications Class-Specific Descriptors	412
Communications Class-Specific Requests.....	412
Display Device Class.....	412
The Standard Display Device Class Interface.....	413
Display Device-Specific Descriptors	413
Device-Specific Requests.....	414
Mass Storage Device Class	414
Standard Mass Storage Interface	415
Control Endpoint	415
Bulk Transfer Endpoints.....	416
Interrupt Endpoint.....	416
General Mass Storage Subclass.....	416
CD-ROM Subclass.....	416
Tape Subclass.....	417
Solid State Subclass.....	417
Class- and Device-Specific USB Requests	418

Contents

Part Six USB Software Overview

Chapter 22: Overview of USB Host Software

USB Software	421
Function Layer.....	422
Device Layer	422
Interface Layer.....	423
The Software Components	424
USB Driver (USB D)	426
Configuration Management	426
USB Elements Requiring Configuration	426
Allocating USB Resources.....	427
Verifying Power	427
Tracking and Allocating Bus Bandwidth.....	428
Bus Bandwidth Reclamation	429
Data Transfer Management	429
Providing Client Services (The USB Driver Interface)	430
Pipe Mechanisms	430
Client Pipe Requirements.....	430
Command Mechanisms	431

Appendix

Appendix A: Standard Device Requests

Overview	435
Standard Device Requests	436
Set/Clear Feature	439
Device Remote Wakeup.....	439
Endpoint Stall	439
Set/Get Configuration	440
Set/Get Descriptor	440
Set/Get Interface	441
Get Status	442
Device Status.....	442
Self-Powered Bit.....	442
Remote Wakeup Bit.....	443
Port Test Bit.....	443
Endpoint Status	443

Sync Frame	444
Device Tests	444
High-speed Driver/Receiver Compliance Testing	444
Activating Test Mode	444

Appendix B: Hub Requests

Overview.....	447
Hub Request Types	448
Standard Requests and Hub Response	449
Hub Class Requests	450
Get/Set Descriptor Request.....	452
Get Hub Status Request.....	452
Hub Status Fields.....	453
Local Power Status	453
Over-Current Indicator	453
Hub State Change Fields.....	454
Local Power Status Change	454
Over-Current Indicator Change	454
Set/Clear Hub Feature Request	455
Hub Local Power Change Request.....	456
Hub Over-Current Change Request.....	456
Get Port Status Request	456
Port Status Fields.....	457
Current Connect Status Field	457
Port Enabled/Disabled	457
Suspend	458
Over-Current Indicator	458
Reset.....	458
Port Power	458
Low-Speed Device Attached	459
High-Speed Device Attached.....	459
Port Test	459
Port Indicator Control	459
Port Change Fields.....	459
Current Status Change	460
Port Enable/Disable Change	460
Suspend Change (Resume Complete)	460
Over-Current Indicator Change	461
Reset Complete.....	461
Set/Clear Port Feature.....	461
Port Test Modes.....	462
Get Bus State	463

Contents

Appendix C: Universal Host Controller

Overview.....	465
Universal Host Controller Transaction Scheduling	465
Universal Host Controller Frame List Access.....	466
UHC Transfer Scheduling Mechanism	467
Bus Bandwidth Reclamation	468
Transfer Descriptors	468
Queue Heads.....	473
UHC Control Registers	474

Appendix D: Open Host Controller

Overview.....	477
Open Host Controller Transfer Scheduling	477
The Open Host Controller Transfer Mechanism.....	478
The ED and TD List Structure.....	480
Interrupt and Isochronous Transfer Processing.....	480
Control and Bulk Transfer Processing.....	480
The Done Queue	481
Interrupt Transfer Scheduling.....	481
Endpoint Descriptors	483
Transfer Descriptors	485
General Transfer Descriptor	486
Isochronous Transfer Descriptor	488
The Open Host Controller Registers.....	492

1-1	System Resources Used by Legacy Peripheral Devices	14
1-2	Connectors at Backplane	17
1-3	USB Device Connections	22
2-1	USB System Implemented in a PCI-Based Platform	26
2-2	USB Controller Integrated into I/O Hub Chip	27
2-3	1.x Systems Support Only Low- and Full-Speed Devices	28
2-4	Full-Speed Transactions Do Not Reach Low-Speed Devices	29
2-5	Conceptual View of Transaction Generation — Example 1	31
2-6	Conceptual View of Transaction Generation — Example 2	32
2-7	Conceptual View of 1ms Frame Generation	33
2-8	Example of USB Devices That Share Bus Bandwidth	35
2-9	USB 2.0 System with Low-, Full-, and High-Speed Devices Attached	37
2-10	Low- and Full-Speed Devices Attached to Ports of the Root, 1.x, and 2.0 Hubs	38
2-11	Split IN Transaction Sequence	39
2-12	Example 2.0 Controller with Three 1.x Host Controllers Used for Low- and Full-Speed Support	40
2-13	Example of High-Speed Devices Attached to 2.0 Root Hub and High-Speed Hub	41
2-14	Conceptual View of Host Controller Generation of Microframes	42
2-15	Bandwidth Comparison Between 12MHz Frames and 480MHz Microframes	43
2-16	Communication Flow in a USB System	45
2-17	Block Diagram of Major Root Hub Functions	49
2-18	USB Hub Types	50
2-19	Primary Hub Functions	51
2-20	Hub Repeater Performing Downstream and Upstream Connectivity	52
2-21	The Communications Model	56
2-22	USB Devices Performing Transfers During Frame	58
2-23	Relationship Between IRPs, Transfers, Frames, and Packets	59
2-24	Standard Descriptors	61
2-25	Standard Descriptors with Two Configurations	62
2-26	Device Framework — Software’s View of Hardware	64
2-27	USB’s Tiered Star Topology	68
3-1	A View of the Series A Plug	70
3-2	Cross Section of a Low-Speed Cable Segment	72
3-3	Cross Section of a High-Speed Cable Segment	73
4-1	Minimum Cable Voltage and Voltage Drop Budget	78
4-2	Bus-Powered Hub with Embedded Function and Four Ports	82
4-3	Low-Power USB Function	83
4-4	Bus-Powered Function (High Power)	85
4-5	Self-Powered Hub with Embedded Function	88
4-6	Self-Powered Device	90
5-1	Signaling Interface USB Hub and Attached USB Full-Speed Device	95
5-2	Hub Port with No Device Connected	96
5-3	Connect Sequence from Port Power through Device Reset	97
5-4	Full-Speed Device Detection	98
5-5	Signal States During FS Device Attachment	99
5-6	Low-Speed Device Detection	100

Figures

5-7	Line States During Low-Speed Device Connection.....	101
5-8	Signaling State During Device Disconnect.....	102
5-9	Bus Idle Line States.....	103
5-10	Reset Signaling States.....	104
5-11	Signaling Interface Between Hub and Device.....	105
5-12	Full-Speed Differential Drivers and Receivers.....	106
5-13	CMOS Buffer with Series Resistors Achieve Specified Output Impedance.....	107
5-14	Full-Speed Driver and Receiver Waveforms.....	108
5-15	Start of Packet Is Recognized at the Beginning of the Synchronization Sequence.....	109
5-16	Full- or Low-Speed EOP signaling.....	110
5-17	Transfers Across USB Cables Employ NRZI Encoding and Differential Signaling.....	111
5-18	NRZI Encoded Data.....	112
5-19	Stuffed Bit.....	113
5-20	USB Signaling Levels.....	115
6-1	Communications Pipes Between Client Software's Memory Buffer and Device Endpoints.....	120
6-2	Client Request Converted to USB Transactions.....	121
6-3	Isochronous Application Using USB CD-ROM and Speakers.....	126
6-4	Example of Source Device Delivering Isochronous Data to the Bus.....	127
6-5	Example of Sink Device Receiving Isochronous Data from the Bus.....	127
6-6	Format of Feedback Data for Full-Speed Devices.....	133
6-7	Format of Feedback Data for High-Speed Device.....	133
7-1	The Layers Involved in USB Transfers.....	142
7-2	Many USB Transactions Consist of Three Phases.....	143
7-3	Packet Format.....	144
7-4	Synchronization Sequence.....	144
7-5	Packet Identifier Format.....	146
7-6	End of Packet signaling.....	147
7-7	Format of an SOF Packet.....	149
7-8	IN Token Packet Format.....	150
7-9	OUT Token Packet Format.....	151
7-10	SETUP Token Packet Format.....	151
7-11	DATA0 Packet Format.....	152
7-12	DATA1 Packet Format.....	153
7-13	Handshake Packet Formats.....	154
7-14	Preamble Packet Format.....	156
7-15	IN Transaction Without Errors.....	157
7-16	IN Transaction With Data Phase Errors.....	158
7-17	IN Transaction With Target Temporarily Unable to Return Data.....	158
7-18	IN Transaction with Target Stalled.....	159
7-19	IN Transaction During Isochronous Transfer.....	160
7-20	OUT Transaction Without Errors.....	161
7-21	OUT Transaction with Data Packet Errors.....	161
7-22	OUT Transaction to Target That is Unable to Accept Data.....	162
7-23	OUT Transaction to Stalled Endpoint.....	162
7-24	OUT Transaction During Isochronous Transfer.....	163

7-25	Format of a Two Stage Control Transfer	165
7-26	Control Transfer Requesting Data from Target.....	165
7-27	Control Transfer Issuing a Command to a Target's Control Endpoint	166
8-1	PID Check	169
8-2	Total Trip Delay	173
8-3	OUT Transaction With Data Toggle Sequence and No Errors.....	177
8-4	IN Transaction With Data Toggle Sequence and No Errors.....	179
8-5	OUT Transaction With Data Toggle and Data Packet Errors	180
8-6	IN Transaction With Data Toggle and Data Packet Errors.....	182
8-7	OUT Transaction With Data Toggle and Handshake Errors	184
8-8	IN Transaction With Data Toggle and Handshake Errors	186
8-9	Data Toggle During Control Transfers.....	188
8-10	Hub EOF Points.....	190
8-11	EOF Timing Ranges.....	191
8-12	Hub Repeater State Diagram.....	192
9-1	Host Initiated Resume.....	198
9-2	Global Resume Signaling Due to Wakeup from Target Device.....	200
9-3	Selective Resume Signaled by Target Device	203
9-4	Device Initiated Selective Resume to Suspended Hub.....	205
9-5	Resume with Selective and Global Suspend.....	207
9-6	Repeater State Machine With Suspend and Resume Transitions.....	209
10-1	USB 2.0 Example Topology	215
11-1	High-Speed Capable Ports Must Support a Variety of Speeds.....	218
11-2	High-Speed signaling Interface	220
11-3	Sequence of Events from Device Connect to High-Speed Operation	221
11-4	Chirp Sequence Used to Detect High-Speed Capable Device.....	223
11-5	High-Speed Cable Termination	225
11-6	Interface Elements Used During High-Speed Differential Signaling.....	226
11-7	SOP Detection.....	228
11-8	Test Points	231
11-9	Test Packet Contents.....	232
11-10	Example Eye Diagram for Transmit Test	233
11-11	Example Eye Diagram for Receiver Sensitivity Test	234
11-12	High-Speed Synchronization Sequence and SOP	235
11-13	Squelch Detection Can Cause Hubs to Drop up to Four Bits from Synchronization Sequence	235
11-14	High-Speed EOP Detection	236
11-15	Device Removal is Checked at End of MicroSOF Packet.....	237
11-16	Disconnect Envelope Detector	238
12-1	Bandwidth Difference Between Full-Speed Frame and High-Speed Microframe.....	243
12-2	Isochronous Packet Overhead	245
12-3	Interrupt Transaction Overhead.....	248
12-4	Minimum and Maximum Packet Sizes for High-Bandwidth Transactions.....	251
12-5	Data Packet Sequence Used During High-Bandwidth Isochronous IN Transactions	252

Figures

12-6	Data Packet Sequence Used During High-Bandwidth Isochronous OUT Transactions.....	253
12-7	Bulk Transaction Overhead.....	255
12-8	Control Transfer Overhead - Setup Stage.....	258
12-9	Control Transfer Overhead - Data Stage.....	258
12-10	Control Transfer Overhead - Status Stage.....	259
12-11	PING Transaction versus OUT Transaction.....	261
12-12	Host Ping Processing Overview.....	262
12-13	Endpoint Ping Processing.....	262
13-1	Worst-Case Round Trip Delay Between Host and Function.....	267
13-2	Babbling Device Detection Model.....	269
13-3	Separation of EOF Sample Points.....	270
14-1	Device Detection and Entry into Suspend State.....	273
15-1	Example USB 2.0 Topology with Old and New Hubs.....	278
15-2	Packet Routing Options for High-Speed Hub.....	279
15-3	Split Transaction are Required to Access Low- or Full-Speed Devices That Attach to High-Speed Hubs.....	281
15-4	Example Topology Where Devices Do Not Operate Optimally.....	282
16-1	Repeater Function Within Hub.....	284
16-2	Repeater State Machine.....	287
17-1	Packet Flow Through Hub with LS/FS and HS Devices Attached.....	290
17-2	Example Isochronous OUT Split Transaction.....	292
17-3	Example Isochronous IN Split Transaction.....	293
17-4	Example OUT Split Transaction With Data Delivery Verification.....	294
17-5	Example IN Split Transaction With Data Delivery Verification.....	295
17-6	Split Token Packet Definition.....	297
17-7	Major Elements Within Transaction Translator.....	298
17-8	Example Split Transaction Sequence — Step 1.....	301
17-9	Example Split Transaction Sequence — Step 2.....	302
17-10	Example Split Transaction Sequence — Step 3.....	303
17-11	Example Split Transaction Sequence — Step 4.....	304
17-12	Example Split Transaction Sequence — Step 5.....	305
17-13	Example Split Transaction Sequence — Step 6.....	306
17-14	Example Split Transaction Sequence — Step 7.....	307
17-15	Example Split Transaction Sequence — Step 8.....	308
17-16	Example Split Transaction Sequence — Step 9.....	309
17-17	Single or Multiple Transaction Translators.....	310
17-18	Periodic Split Transaction Pipeline.....	311
17-19	Isochronous Start Split Packet Sequence.....	313
17-20	Start-Split Encoding for Isochronous OUT Transactions.....	314
17-21	Sequence of Packets in Start-Split Transaction During Isochronous IN.....	316
17-22	Sequence of Complete-Split Transaction During Isochronous IN.....	318
17-23	Interrupt OUT Start-Split Packet Sequence.....	320
17-24	Interrupt OUT Complete-Split Packet Sequence.....	321
17-25	Interrupt IN Start Split Sequence.....	323
17-26	Complete Split Transaction Sequence During an Interrupt IN transaction.....	324

17-27	Non-Periodic Split Transaction Pipeline	327
17-28	Bulk/Control OUT Start-Split Sequence	329
17-29	Bulk/Control OUT Complete-Split Sequence	331
17-30	Bulk/Control IN Start-Split Sequence	333
17-31	Bulk/Control IN Complete Split Sequence.....	335
18-1	The Software Elements Used During Configuration.....	341
18-2	Root Hub's Control and Status Change Endpoints	344
19-1	Hub and Port Status Change Bitmap	350
19-2	Descriptor Tree Containing Alternate Interface Settings.....	365
20-1	Required Hub Endpoints.....	377
20-2	Standard Hub Descriptors.....	378
20-3	Hub and Port Status Change Bitmap.....	398
21-1	CD-ROM Supporting Mass Storage and Audio Interfaces.....	405
22-1	Device Framework — Software's View of Hardware	423
22-2	Software Layers.....	425
A-1	Format of Setup Transaction that Specifies the Device Request Being Performed	436
B-1	Format of Setup Transaction That Specifies the Device Request Being Performed.....	447
C-1	Universal Host Controller Transfer Scheduling.....	466
C-2	Frame List Access.....	467
C-3	Transfer Mechanism and Execution Order	469
C-4	Transfer Descriptor Format	470
C-5	The Queue Head Link and Element Link Pointers.....	473
D-1	USB Transfer Scheduling	478
D-2	The Transfer Scheduling Mechanism	479
D-3	Transfer Queues.....	481
D-4	Interrupt Scheduling	482
D-5	Endpoint Descriptor Format	483
D-6	Transfer Descriptor Format	486
D-7	Isochronous Transfer Descriptor	490
D-8	Open Host Controller Registers.....	493