



SuperSpeed USB Developers Conference

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Protocol Layer

Bart Vertenten

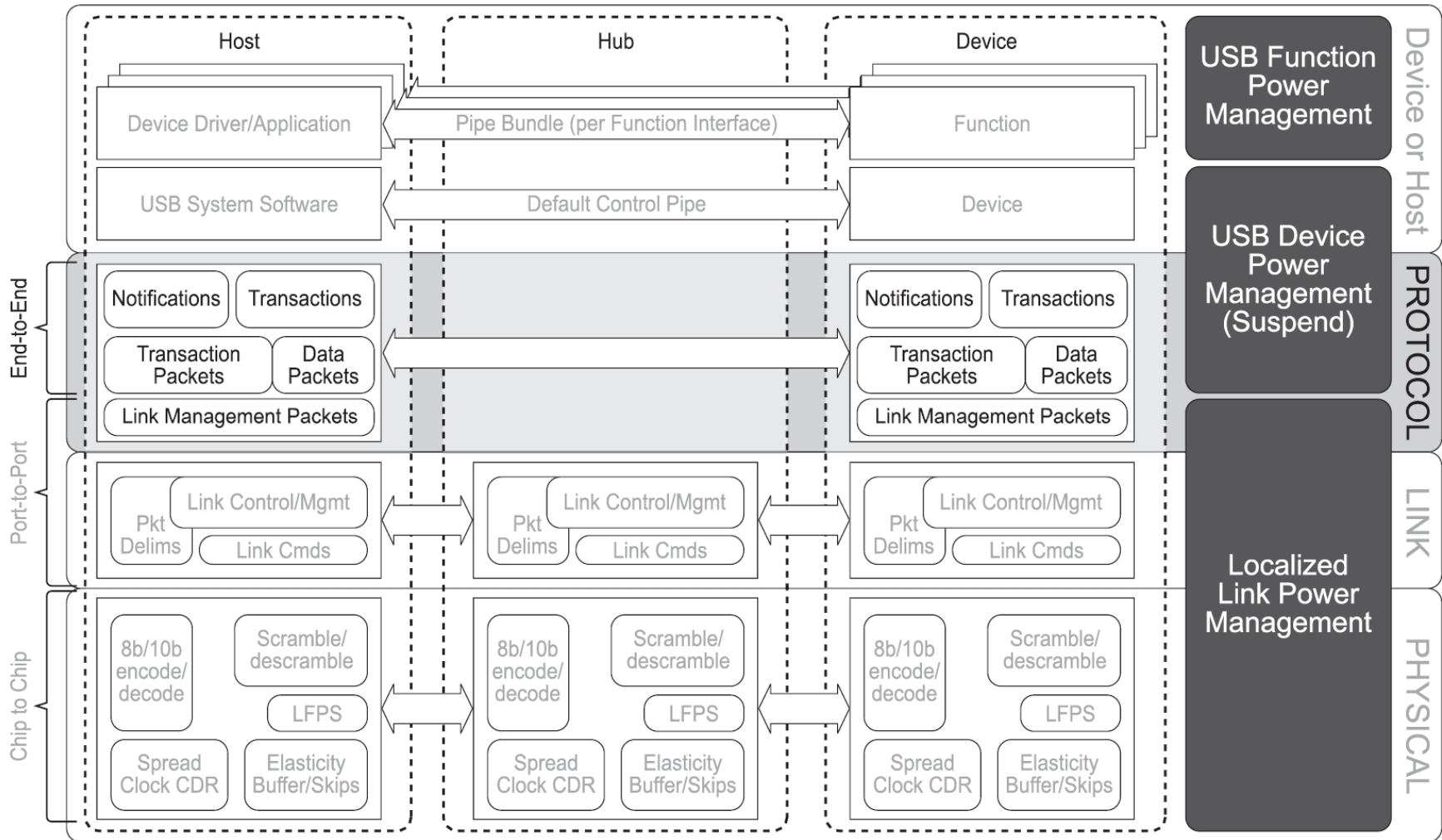
Sr. Architect Connectivity
NXP Semiconductors



Agenda

- Goals
- Packet Flow
- Packet Format
- Packet Types
- Protocol Basics
- Transfer Types
- Summary

Overview



Goals

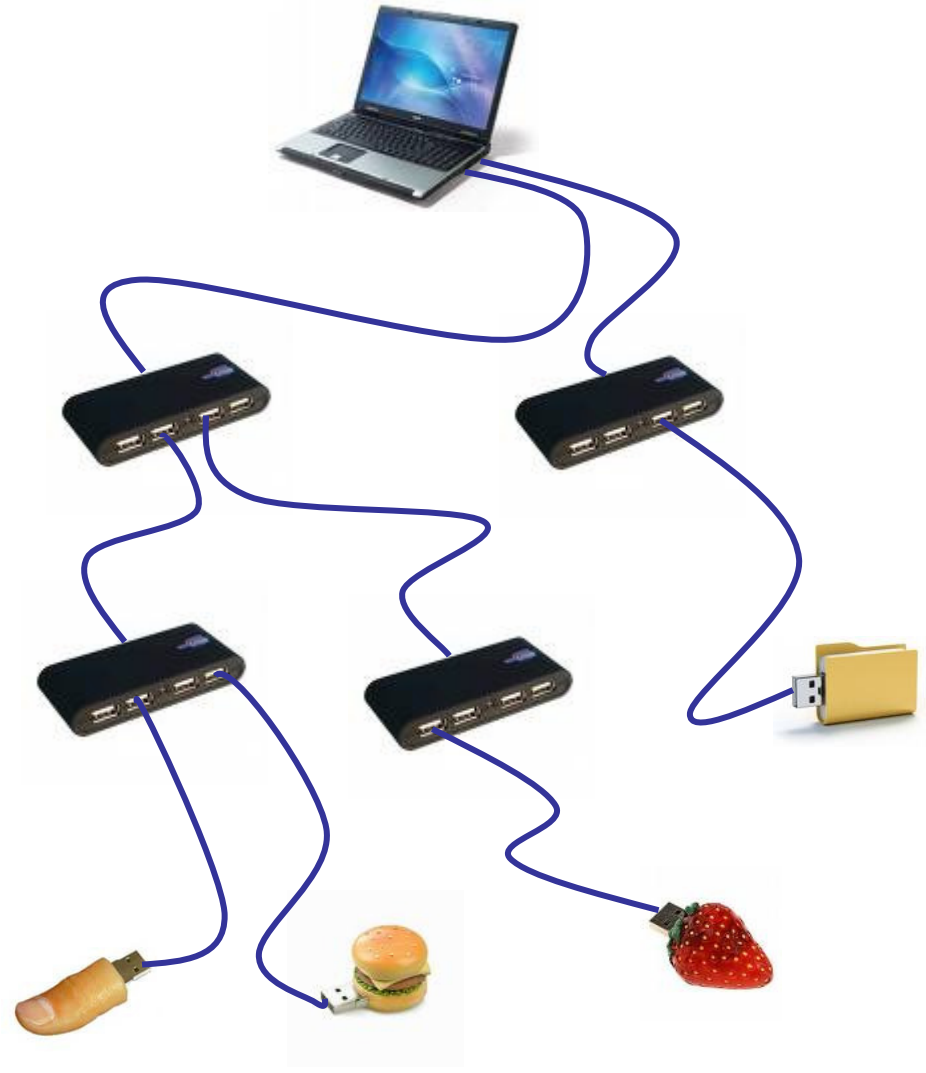


- Preserve USB device model
 - Existing PIPE model
 - All transfer types
 - No polling !
- Backward compatible
 - Existing class drivers continue to work
 - Short Packet and STALL semantics preserved
 - Peripheral device operate exclusively in SuperSpeed or other speed, not both at the same time
- Extensible
 - Designed to scale to at least 25Gb/s
- Power Efficient
 - Provide superb power characteristics (especially for idle links)

Packet Flow



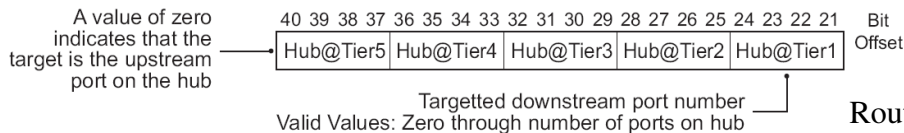
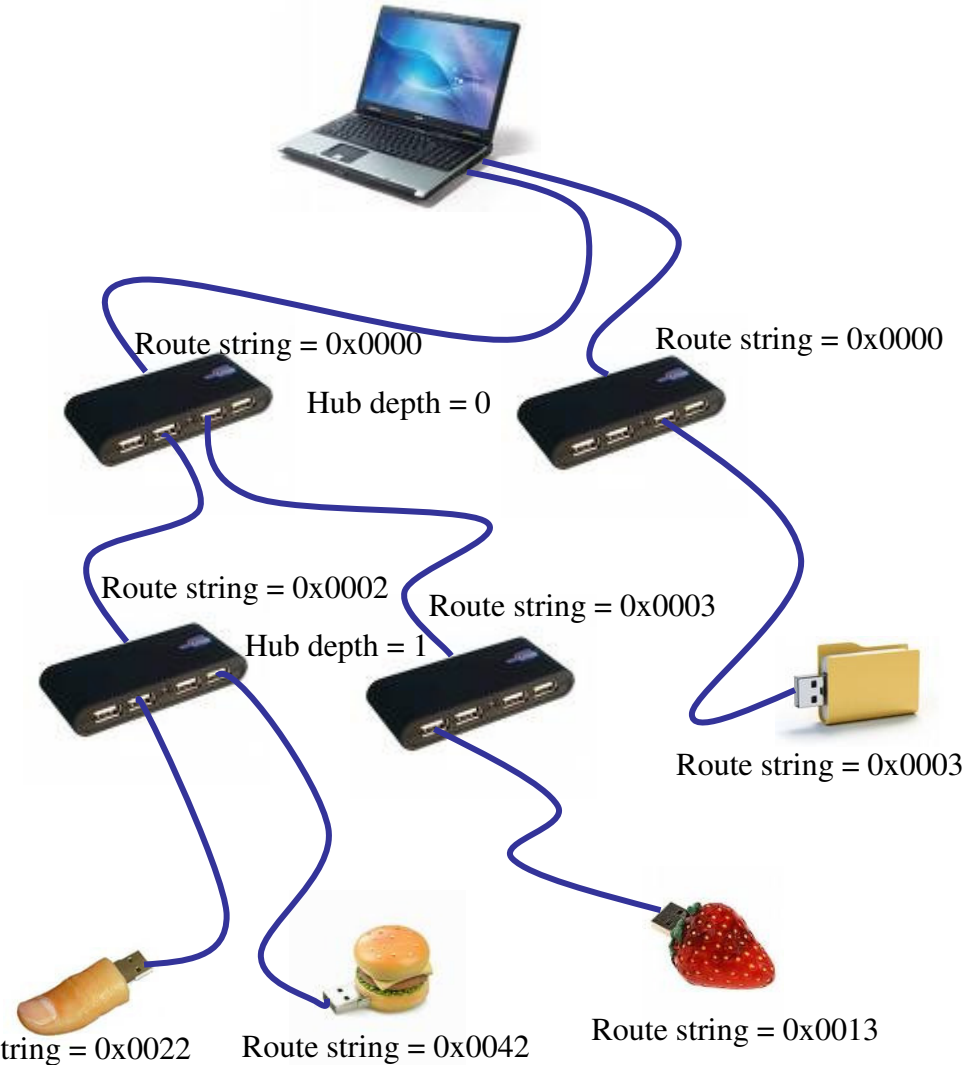
- Packets are not broadcast
- Packets traverse only the link-pairs between host and device
- Downstream packets use route string information
- Upstream packets have always the host as destination



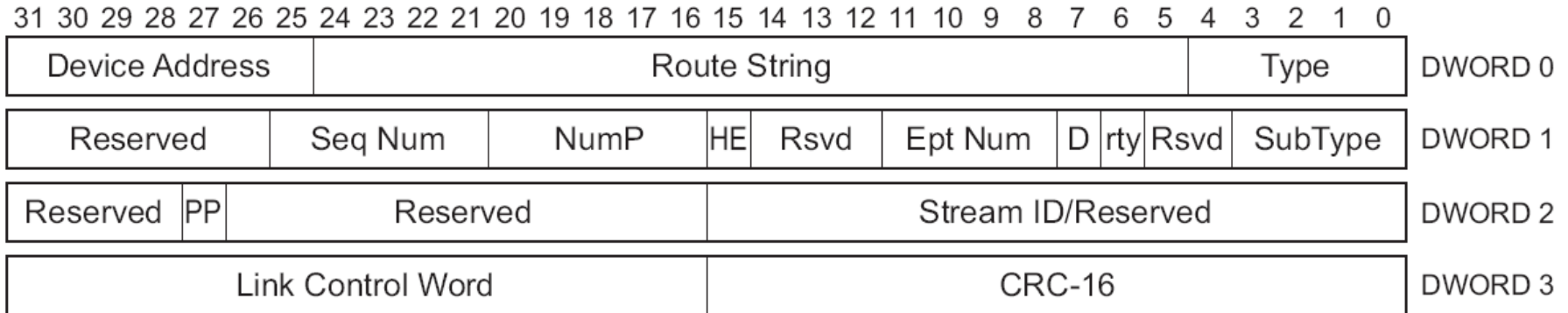
Route string



- Consists of a concatenation of 4-bit Sub-Strings
- Route sub-string
 - Value identifies target port
 - Zero reserved for upstream port
 - Non-zero values represent individual downstream ports
- Route string index
 - Hub is given its depth during enumeration
 - Route String index equals Hub Depth x 4



Packet Format



- Reserved fields
 - Transmitter : shall set to zero
 - Receiver : shall ignore
- Type field : LMP, TP, DP, ITP
 - Defines format of the packet
- CRC-16
 - Calculated over the preceding 12 bytes of the packet header
- Link Control Word
 - Port-to-port control info (see Link Layer presentation for more information)



Packet Types

- Link Management Packets (LMP)
- Transaction Packets (TP)
- Data Packet (DP)
- Isochronous Timestamp Packet (ITP)

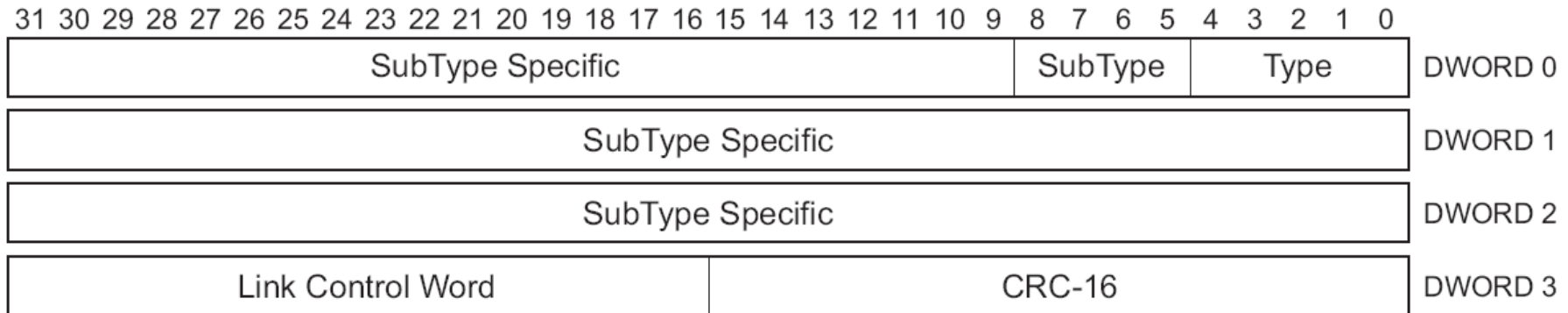


Packet Types

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Packet Types

Link Management Packet



- Subtypes

- Set Link Function
- U2 Inactivity Time-out
- Vendor Device Test
- Port Capability
- Port Configuration
- Port Configuration Response

Link Management Packet

Set Link Function



- Only used for compliance and test modes
- Force a link to always accept LGO_U1 and LGO_U2 link commands
- This LMP is sent by a hub upon receipt of SetPortFeature (FORCE_LINKPM_ACCEPT)
- Software must ensure that there are no pending packets at the link level before issuing a SetPortFeature command that generates an LGO_U1 or LGO_U2 link command.

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Reserved																Set Link Function				SubType		Type		DWORD 0								
Reserved																																DWORD 1
Reserved																																DWORD 2
Link Control Word																CRC-16																DWORD 3

Link Management Packet Vendor Device Test



- Used for vendor-specific device testing
- Shall not be used during normal operation of the link

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Reserved																Vendor Device Test				SubType		Type		DWORD 0								
Vendor Defined Data																																DWORD 1
Vendor Defined Data																																DWORD 2
Link Control Word																CRC-16																DWORD 3

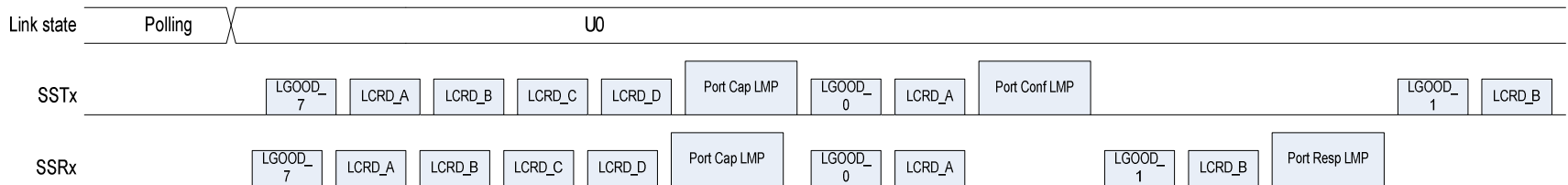
Link Management Packet Port Capability



- Sent by both link partners after successful completion of training and link initialization
 - Only after warm-reset or power-on reset
- To be sent within tPortConfiguration time after completion of link initialization
- Fields
 - Link Speed fixed to 0x1 (supports 5Gb/s signaling)
 - Num HP Buffers fixed to 0x4
 - Direction bit 0 = downstream support
bit 1 = upstream support
 - Tie-breaker

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0																		
Reserved										Link Speed				SubType		Type		DWORD 0
Reserved				Tiebreaker		R	D	Reserved				Num HP Buffers				DWORD 1		
Reserved																DWORD 2		
Link Control Word										CRC-16						DWORD 3		

Port Configuration / Response Examples



SS Tx	Packet	Dir	S	LMP	SubType	Link Speed	Nm HP Bfrs	Direction	Value
	24	-->	S		Port Capability	5Gbs	4	Down	0

SS Rx	Packet	Dir	S	LMP	SubType	Link Speed	Nm HP Bfrs	Direction	Value
	25	<--	S		Port Capability	5Gbs	4	Up	0

SS Tx	Packet	Dir	S	LMP	SubType	Link Speed	Direction
	26	-->	S		Port Config	5Gbs	Up

SS Rx	Packet	Dir	S	LMP	SubType	Ack Code
	27	<--	S		Port Cfg Ack	Speed, Type

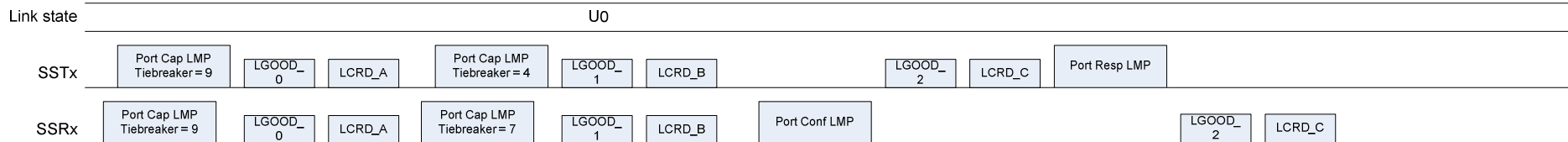
Port Configuration / Response Tiebreaker example



- Tiebreaker value only used when both ports announce to have upstream and downstream capabilities

		Port 2		
		Upstream Only	Downstream Only	Both
Port 1	Upstream Only	Not Defined	Port 2 is the downstream port.	Port 2 is the downstream port.
	Downstream Only	Port 1 is the downstream port.	Not Defined	Port 1 is the downstream port.
	Both	Port 1 is the downstream port.	Port 2 is the downstream port.	The port with the higher value in the Tiebreaker field shall become the downstream port ¹ .

Note: ¹If the **TieBreaker** field contents are equal, then the two link partners shall exchange Port Capability LMPs again with new and different value in the **TieBreaker** field. The sequence of TieBreaker field values generated by a port shall be sufficiently random.





Packet Types

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Packet Types

Transaction Packet

- Typical TP contains following info
 - Type = TP and Sub Type
 - RouteString, DeviceAddress, Endpoint Num, Seq#, NumP

Sub Types

- ACK
- NRDY
- ERDY
- Status
- Stall
- Device Notification
- Ping
- Ping Response

TP	Type	ACK	Route String	ADDR	ENDP	SeqN	Dir	NumP	Stream ID	Pkts Pending
	TP	1	0	1	1	0	H->D	0	0x00000000	Not Pnd

TP	Type	NRDY	Route String	ADDR	ENDP	Dir	Stream ID
	TP	2	0	1	1	H->D	0x00000000

TP	Type	ERDY	Route String	ADDR	ENDP	SeqN	Dir	NumP	Stream ID
	TP	3	0	1	1	0	H->D	0	0x00000000

TP	Type	Status	Route String	ADDR	ENDP	Dir
	TP	4	0	1	1	H->D

TP	Type	Stall	Route String	ADDR	ENDP	Dir
	TP	5	0	1	1	H->D

TP	Type	Dev Notif	Route String	ADDR	Notif Type	Interface
	TP	6	0	1	FUNCION_WAKE	0x00

TP	Type	Ping	Route String	ADDR	ENDP	Dir
	TP	7	0	1	1	H->D

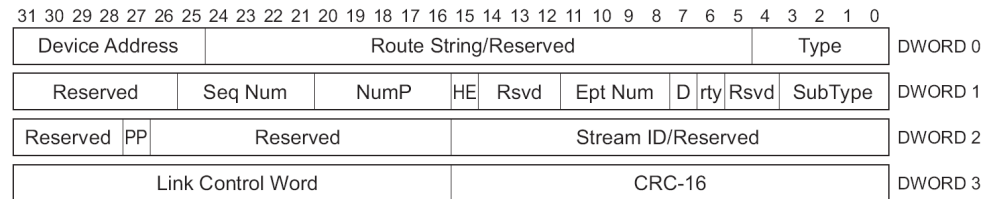
TP	Type	Ping Resp	Route String	ADDR	ENDP	Dir
	TP	8	0	1	1	H->D

Sample Transaction Packet ACK



- Behaviour

- IN endpoints :
 - Acknowledge previous data
 - Request new data
- OUT endpoints :
 - Acknowledge previous data
 - Number of data packet buffers available



- Fields

- RTY = Retry
 - Set if no data packet or corrupted data packet was received
- HE = Host Error
 - Set by host if a valid data packet was not received due to an internal host error
- PP = Packets Pending
 - Only set by host. Used by device for power management
- NumP = Number of Packets
 - NumP = 0 by device triggers a flow control

Device response to ACK TP

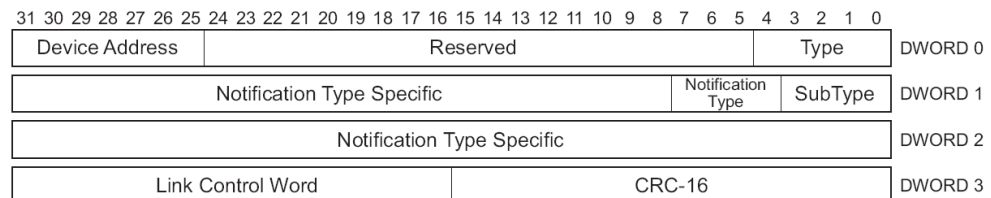


Invalid TP Received	TP Received with Deferred Bit Set	Device Tx Endpoint Halt Feature Set	Device Ready to Transmit Data	Action Taken
Yes	Do not care	Do not care	Do not care	The device shall ignore the TP.
No	Yes	Yes	Do not care	The device shall send an ERDY TP.
No	Yes	No	No	The device shall not respond. It shall send an ERDY TP when it is ready to resume.
No	Yes	No	Yes	The device shall send an ERDY TP indicating that it is ready to send data.
No	No	Yes	Do not care	Issue STALL TP
No	No	No	No	Issue NRDY TP
No	No	No	Yes	Start transmitting DPs with sequence numbers requested by the host

Sample Transaction Packet Device Notification



- Used for Device level notifications
 - Function Wake
 - Latency Tolerance Message (LTM)
 - Bus Interval Adjustment Message
- Fields
 - Function Wake – Interface
 - Indicates interface that signals a remote wakeup
 - LTM – Best Effort Latency Tolerance (BELT)
 - See session on “Power Management” for more info
 - Bus Interval Adjustment
 - Increase/decrease length of bus interval
 - Synchronization of host’s bus interval clock with device external clock
 - See session on “Isochronous” for more info



Sample Transaction Packet

Ping / Ping Response



- Ping

- Sent by the host
- Bring all links between host and device to U0
- Sent prior to sending ISO packet

- Ping Response

- Sent by the device
- Must be sent within tPingResponse time after reception of Ping TP
- Must sent a Ping Response for each received Ping
 - See session on “Isochronous” for more info

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0																															
Device Address										Route String																Type					DWORD 0
Reserved															EPT Num			D	RsvdP		SubType					DWORD 1					
Reserved																															DWORD 2
Link Control Word															CRC-16																DWORD 3

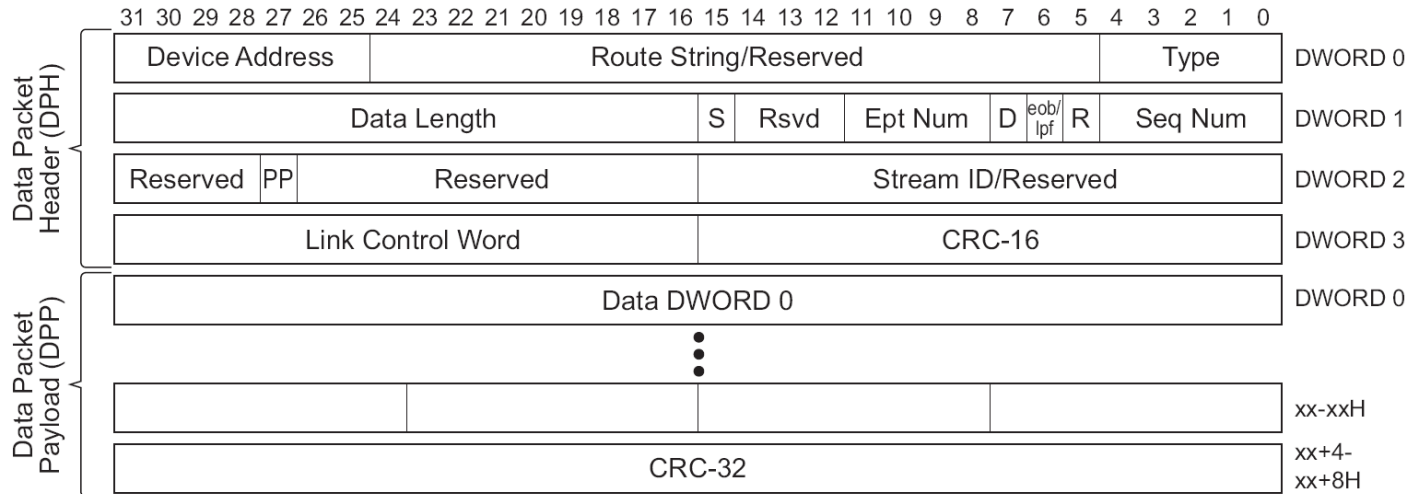


Packet Types

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Packet Types

Data Packet



- EOB / LPF = End of Burst / Last Packet Flag
 - EOB is used for non-isochronous endpoints
 - Device sets this to trigger a flow-control event
- S = Setup
 - Indicates that this DP is a SETUP data packet (Data Length = 8 bytes)
- Data Length
 - Length of data packet payload (excludes CRC-32)

Host response to DP from device



DPH has Invalid Values	Data Packet Payload Error	Host Can Accept Data	TP Returned by Host
Yes	Do not care	Do not care	Discard data and do not send any TP.
No	Yes	Do not care	Discard data and send an ACK TP with the Retry bit set requesting for one or more DPs with the Sequence Number field set to the sequence number of the DP that was corrupted.
No	No	No	Discard data; send an ACK TP with the Retry bit set requesting for one or more DPs with the Sequence Number field set to the sequence number of the DP that the host was unable to receive. The ACK TP shall have the Host Error bit set to one to indicate that the host was unable to accept the data.
No	No	Yes	Accept data and send an ACK TP requesting for zero or more DPs with the Sequence Number field set to the sequence number of the next DP expected. This is also an implicit acknowledgement that this DP was received successfully.

Device response to DP from host



DPH has Invalid Values	DPH has Deferred Bit Set	Receiver Halt Feature Set	Data Packet Payload Error	Device Can Accept Data	TP Returned by Device
Yes	Do not care	Do not care	Do not care	Do not care	Discard DP.
No	Yes	Yes	Do not care	Do not care	The device shall send an ERDY TP.
No	Yes	No	Do not care	No	The device shall not respond. It shall send an ERDY TP when it is ready to resume.
No	Yes	No	Do not care	Yes	The device shall send an ERDY TP.
No	No	Yes	Do not care	Do not care	The device shall send a STALL TP.
No	No	No	Do not care	No	Discard DP, send an NRDY TP.
No	No	No	Yes	Yes	Discard DP, send an ACK TP with the sequence number of the DP expected (thereby indicating that the DP was not received), the Retry bit set and the number of DPs that the device can receive for this endpoint.
No	No	No	No	Yes	Send an ACK TP indicating the sequence number of the next DP expected (thereby indicating that this DP was received successfully) and the number of DPs that the device can receive for this endpoint.

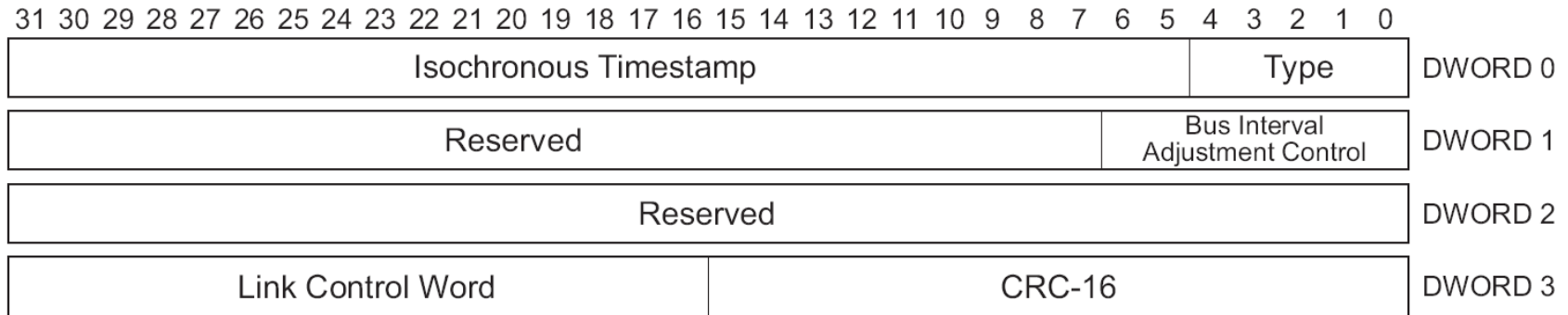


Packet Types

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Packet Types

Isochronous Timestamp Packet



- Used to deliver timestamps from host to all active devices
- No routing information
 - Multicast packet sent by hub to all downstream ports in U0
- Can be sent between packets in a burst

Protocol Basics



- Transfer based data flow rather than Transaction based
 - Transfers happen by moving packets
 - Devices have 'N' data packet buffers
- Data integrity and flow control use transaction packets
 - Host and device responsible for saving and retrying data until 'ACK' received
 - Intermediate hubs do not guarantee data delivery
 - Headers are guaranteed
- After NRDY, ACK(NumP = 0) or DP (EoB = 1), host expects ERDY TP
 - Eliminates the need for polling
- Stall semantics retained
- Short packet semantics retained
- End of Burst / Last Packet Flag
- StreamID added for bulk endpoints



Host Controller requirements

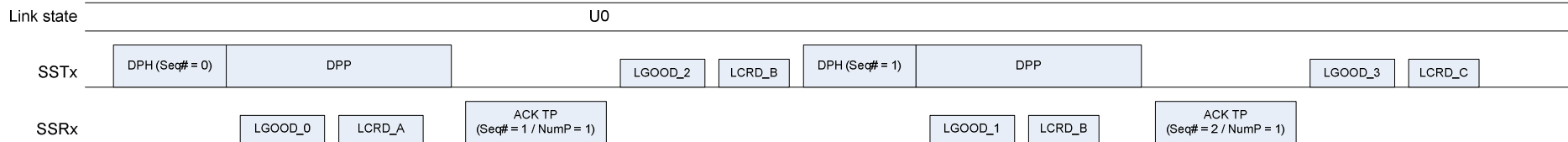
- Host may initiate one or more OUT transactions to one or more endpoints while it waits for the completion of the current bus transaction
- Host shall not initiate another IN transaction to any endpoint until it
 - Receives a DP or NRDY or STALL TP or transaction times out for the current ACK TP sent to a non-isochronous endpoint
 - Receives all the DPs that were requested or it receives a short packet with last packet field set or transaction times out for the current ACK TP sent to an isochronous endpoint

Basic OUT transfer

Single packet



Host / Hub

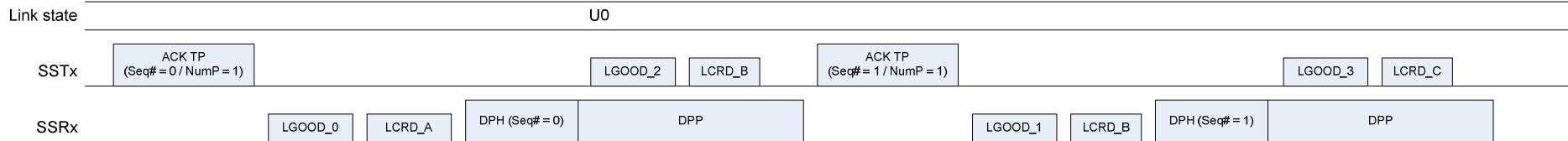


- Host just starts sending data when buffer is queued
- Device returns ACK TP with next expected Seq#
 - Correct data packet : next Seq# = (received Seq# + 1) mod 32
 - Wrong/corrupted data packet : next Seq# = expected Seq#

Basic IN transfer Single packet

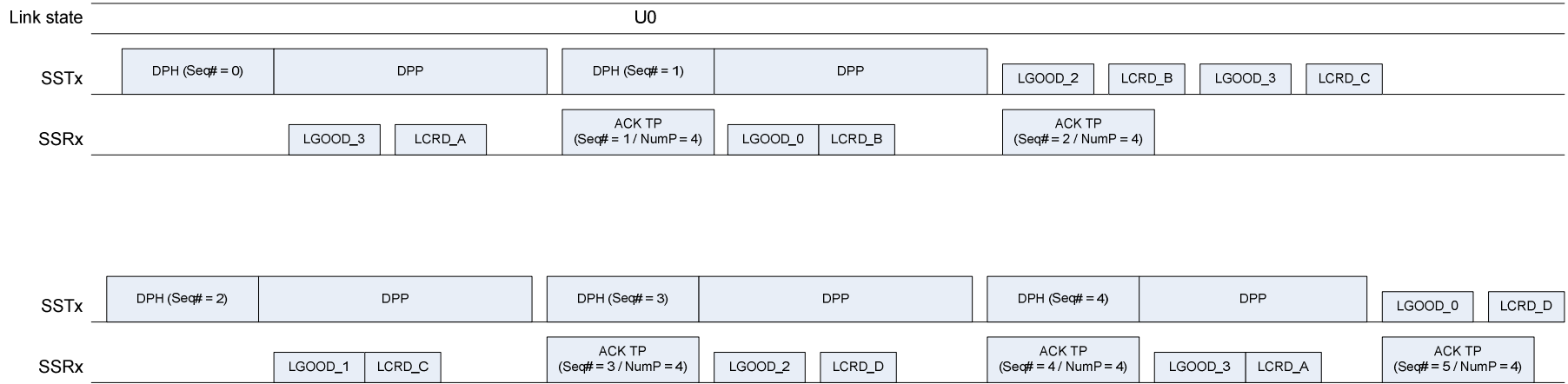


Host / Hub



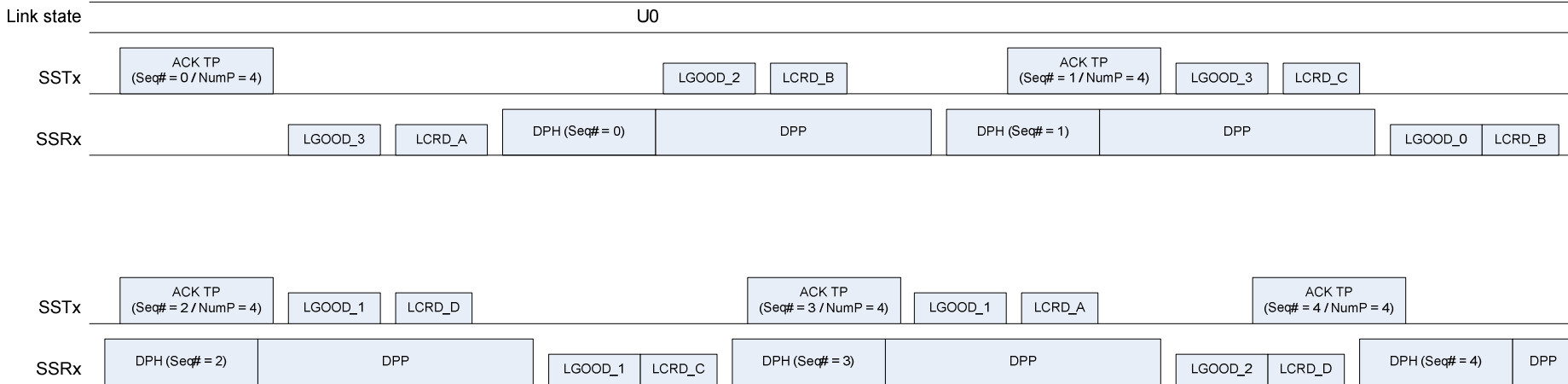
- Host sends ACK TP with expected Seq#
- Device sends data packet with corresponding Seq#

Burst OUT transactions



- NumP indicates the maximum number of packets a device can still receive.

Burst IN transactions

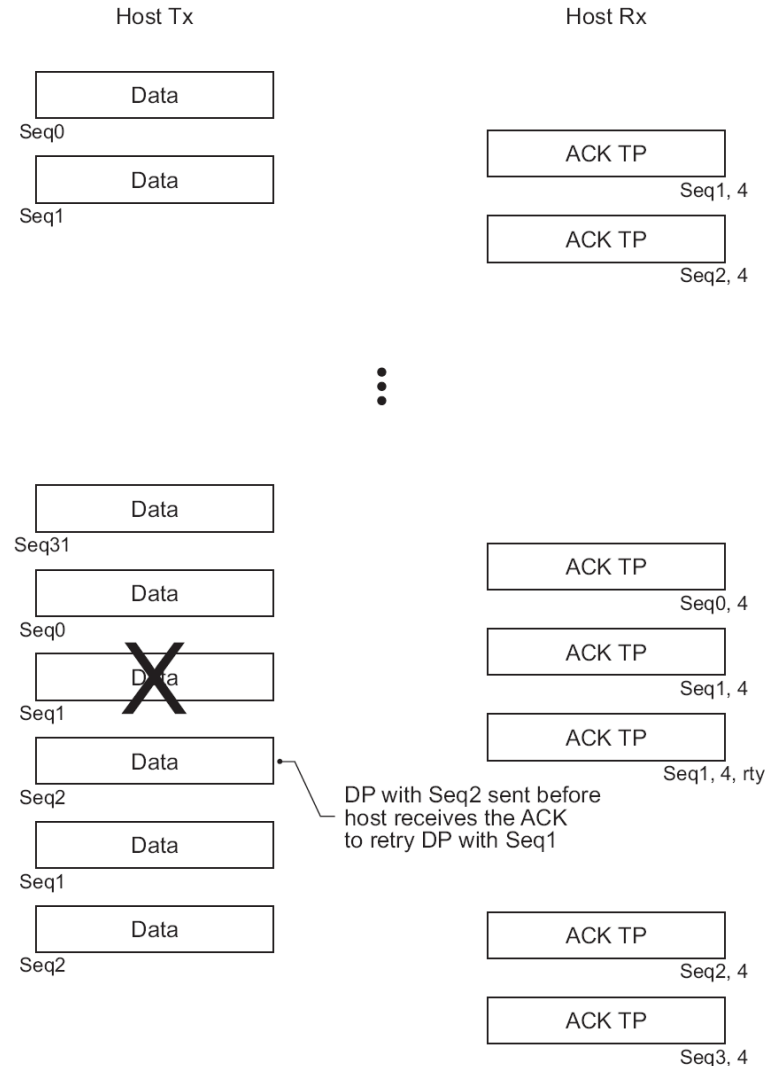


- As long as the host has enough data to transfer, it keeps NumP set to maximum burst size
- Device can send maximum NumP packets without receiving an ACK TP
 - Last sequence number a device can send is $(ACK_TP.Seq\# + ACK_TP.NumP - 1) \bmod 32$

Retry OUT transaction



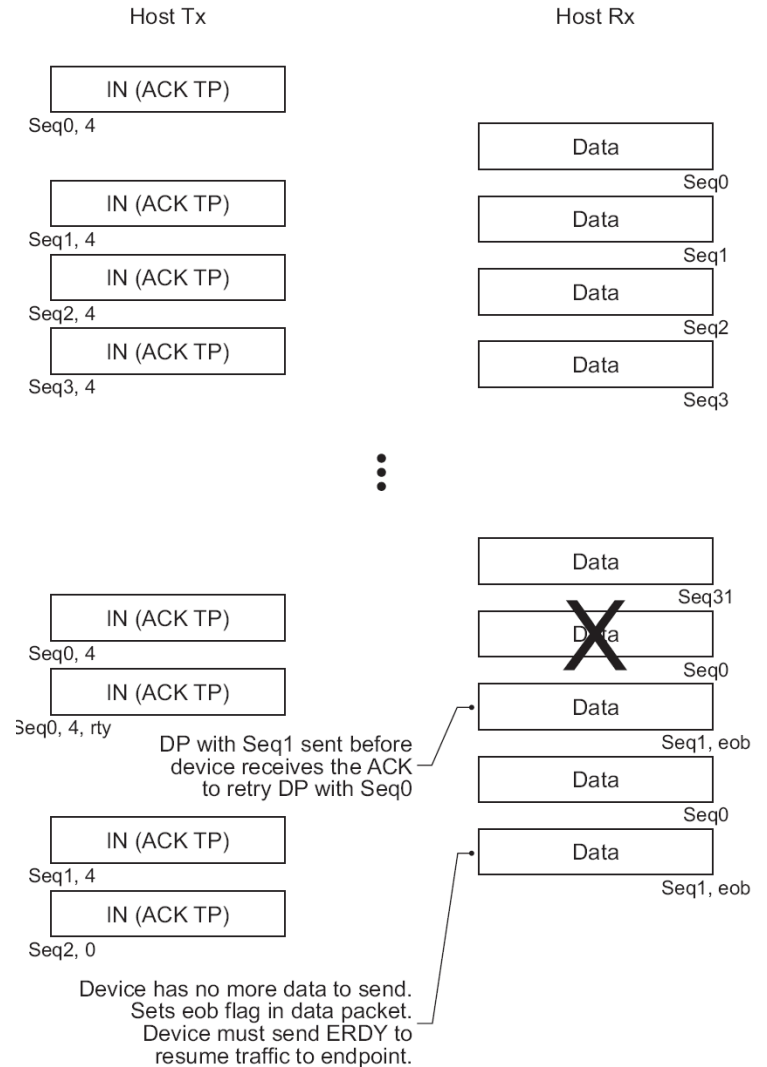
- Retry bit in ACK TP is set when
 - Received corrupted data packet
 - Received data packet with unexpected sequence number
- Upon reception of ACK TP with retry bit
 - Resend data packets starting from sequence number indicated in ACK TP



Retry IN transaction



- Similar as OUT



Flow Control



- IN endpoint
 - Responding with a NRDY TP
 - Sending a DP with EOB field set to '1' in the DPH
- OUT endpoint
 - Responding with a NRDY TP
 - Sending an ACK TP with NumP field to set '0'
- Endpoint must send ERDY to resume service



Short packets

- Short packet completes transfer
- What
 - Datalength value is smaller than MaxPacketSize for that endpoint
- IN endpoint
 - A device shall stop sending DP's after a short DP
 - A host shall send an ACK
 - with NumP = 0
 - or higher (if a new transfer is scheduled)
- OUT endpoint
 - Host may stop sending DP's after sending a short DP
 - Host shall schedule new DP's to the endpoint when a new transfer is initiated



Transfer Types

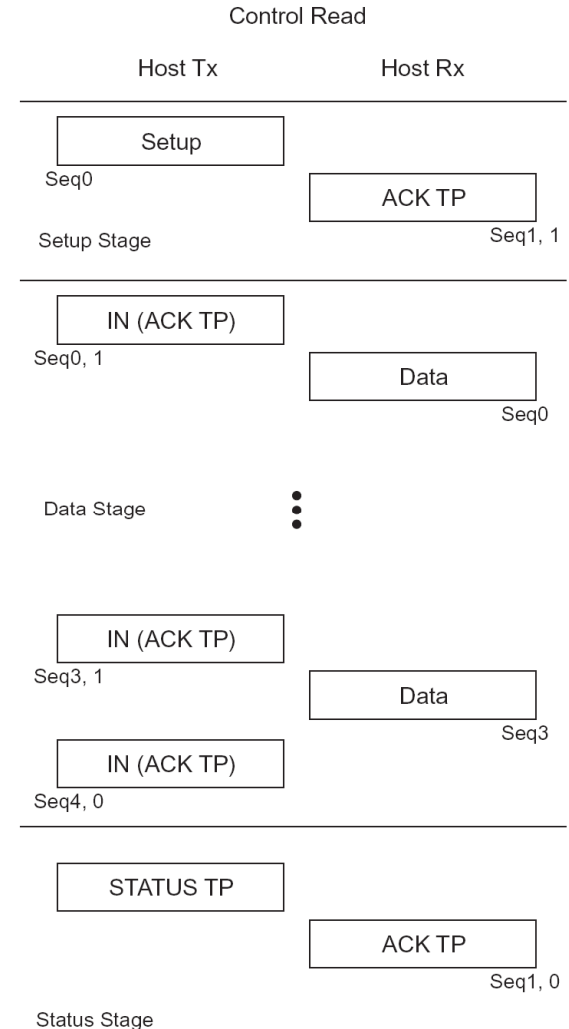
- Control
- Interrupt
- Isochronous
- Bulk

Transfer Types

Control Read



- Setup stage
 - Similar format as bulk OUT
 - Must use sequence number 0
- Data stage
 - Must start with sequence number 0
 - Must return final ACK TP after last data is received before going to status stage
- Status stage
 - ACK must contain sequence number 1
- Direction field for all TP and DP towards/from control endpoint, must be set to 0

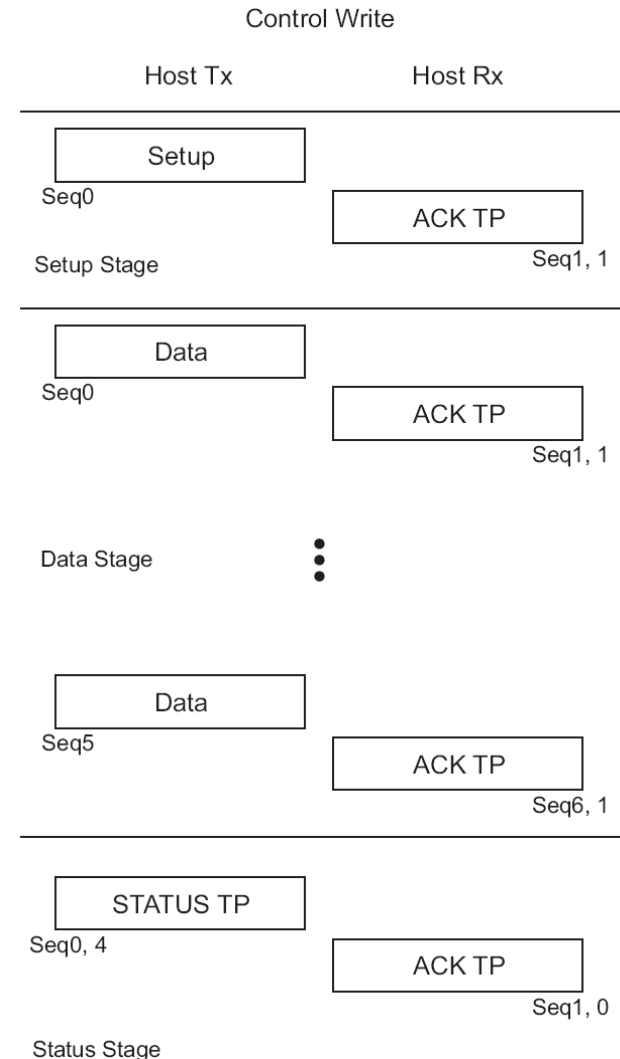


Transfer Types

Control Write



- Setup and status stage are the same as for control read
- Data stage
 - Must start with sequence number 0
 - Host starts sending data after receiving ACK on setup



Transfer Types

Interrupt



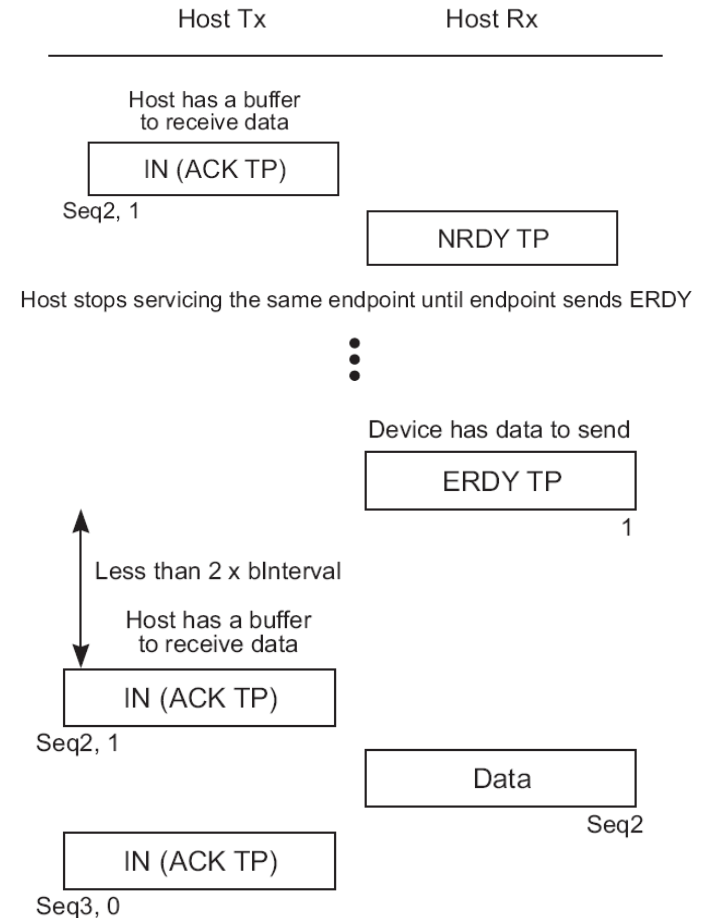
- Bus level protocol is bulk (handshake, retries ,...)
- Endpoint requests
 - Bandwidth (Maxpacket Size and number of packets)
 - Service interval
- Retries may be performed in the current or next interval
- Host must send an ACK for every Data Packet successfully received in the service interval



Transfer Types

Interrupt example

- Host guarantees service attempt each service interval
 - Endpoint must send ERDY to resume service
- Host does not provide additional service to endpoint in an interval (beyond endpoint request)

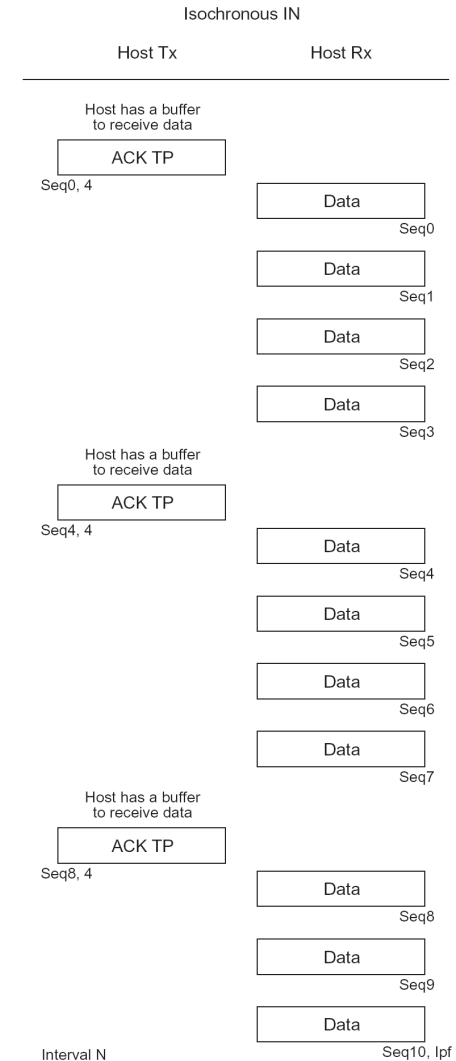
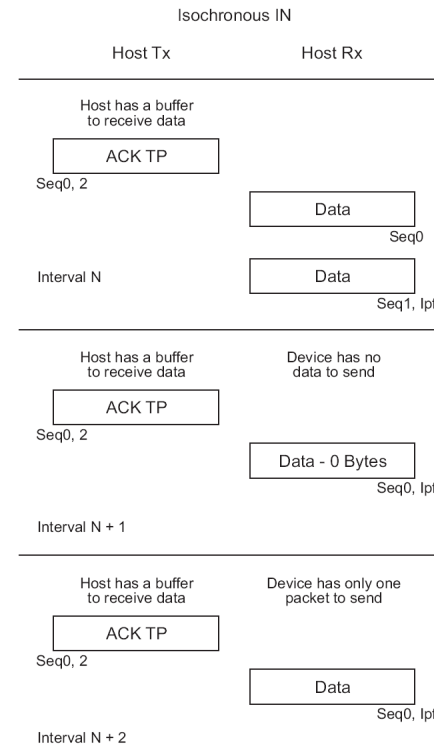




Transfer Types

Isochronous IN

- Host sends ACK TP every interval
- Only one ACK TP for each burst
- No retry on data delivery failure

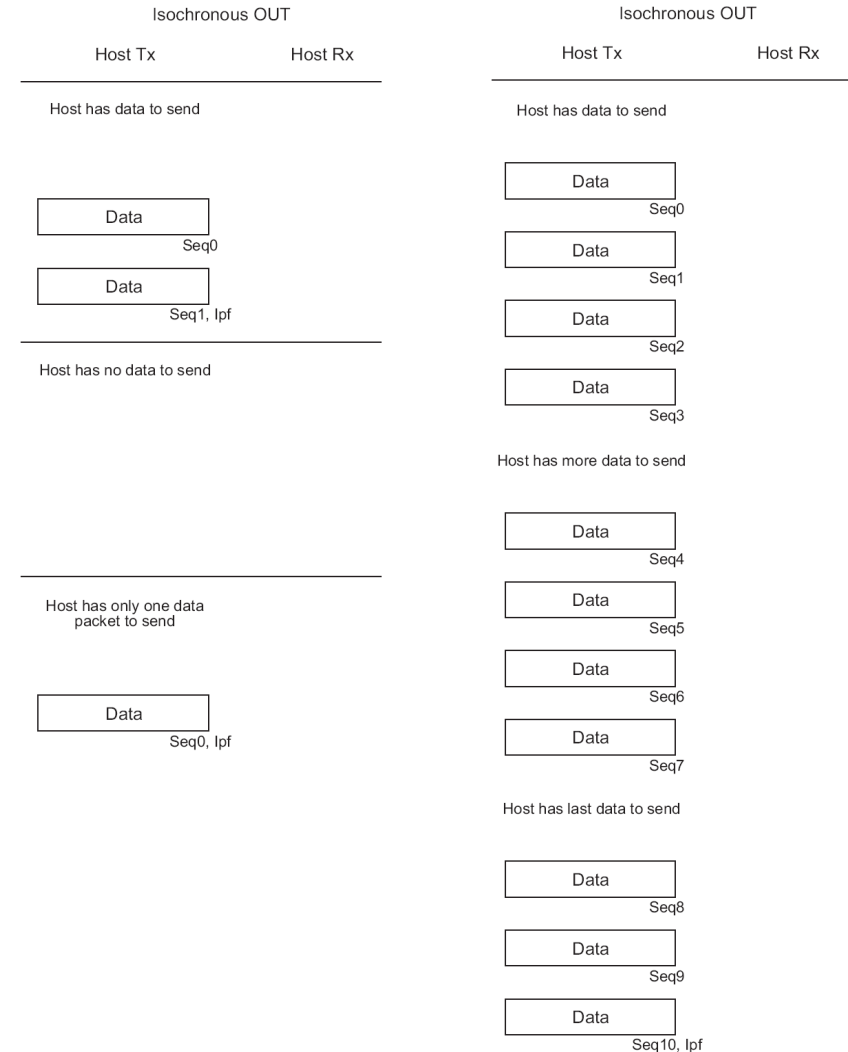




Transfer Types

Isochronous OUT

- Host sends data during each interval
- No ACK from device
- No retry on data delivery failure
- For more information see presentation on “Isochronous”



Transfer Type Bulk



- OUT endpoint
 - Device sends ACK for each valid DP it receives
- IN endpoint
 - Host sends ACK to indicate sequence number and number of packets it expects
 - Host sends ACK TP for each valid DP it receives
 - A device does not need to wait for ACK TP to send next DP

Streaming Protocol



- Up to 64K Streams supported
- Built on top of SS Bulk protocol
 - Requires Stream ID (SID) field in DPH and ACK TP
 - Available on IN and OUT pipes
 - Transfer level multiplexing of data streams
 - Minimize device and host hardware requirements
- Not available on Iso, Interrupt, or Control endpoints
- More information :
 - See session on “Streams”

Summary



- Preserves USB device model, however :
 - NOT a broadcast bus
 - Eliminates the need for Polling
- Preserves Backward compatibility
- Protocol scales with higher bus speeds
- Provides the mechanisms for excellent power efficiency



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