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USB 3.0 Basics

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USB 3.0 Key Features

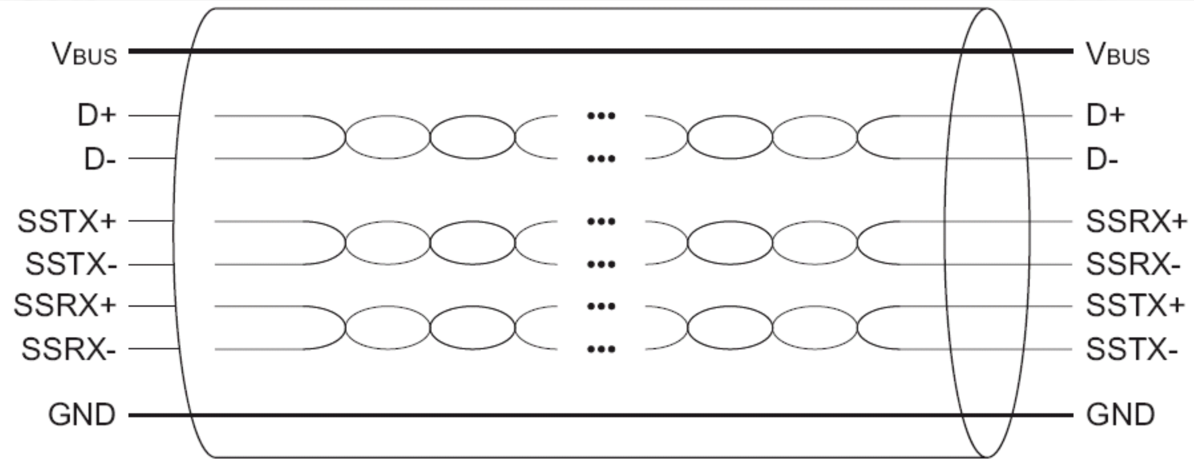
- **Performance of 5GBit/s**
  - Scalability to achieve higher data rates in future
- **Same USB Device Model as for USB 2.0**
- **Backward compatibility**
- **Designed for Power Efficiency**
- **Definition of logical streams**
- **Optimized usage of bandwidth by using ERDY/NRDY**

Bus Architecture

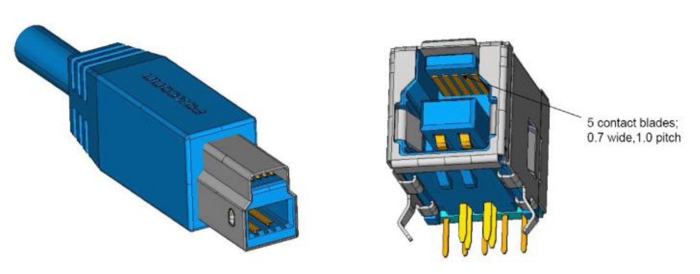
- **New bus architecture is built on top of legacy USB**
  - Operates concurrently with USB 2.0
- **USB 3.0 uses dual-simplex signaling**
  - Asynchronous notifications can be sent by device
- **Packet routing**

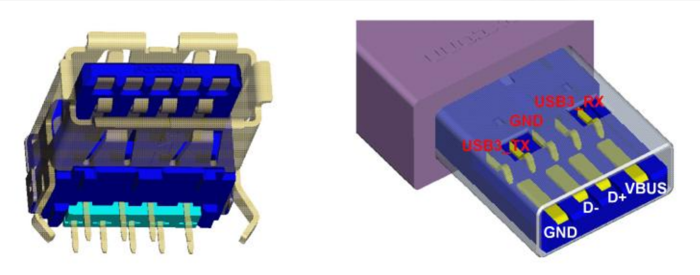
USB 3.0 Cables

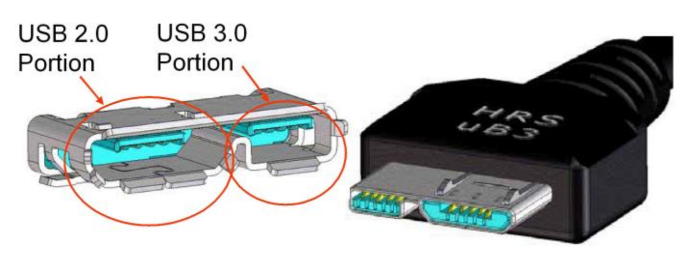
- **Cables contain all wires to support USB 2.0**
  - VDD, GND, D+, D-
- **In addition, USB 3.0 cables have 2 additional twisted pairs for RX/TX**
  - SSTX+, SSTX-, SSRX+, SSRX-



USB 3.0 Connectors







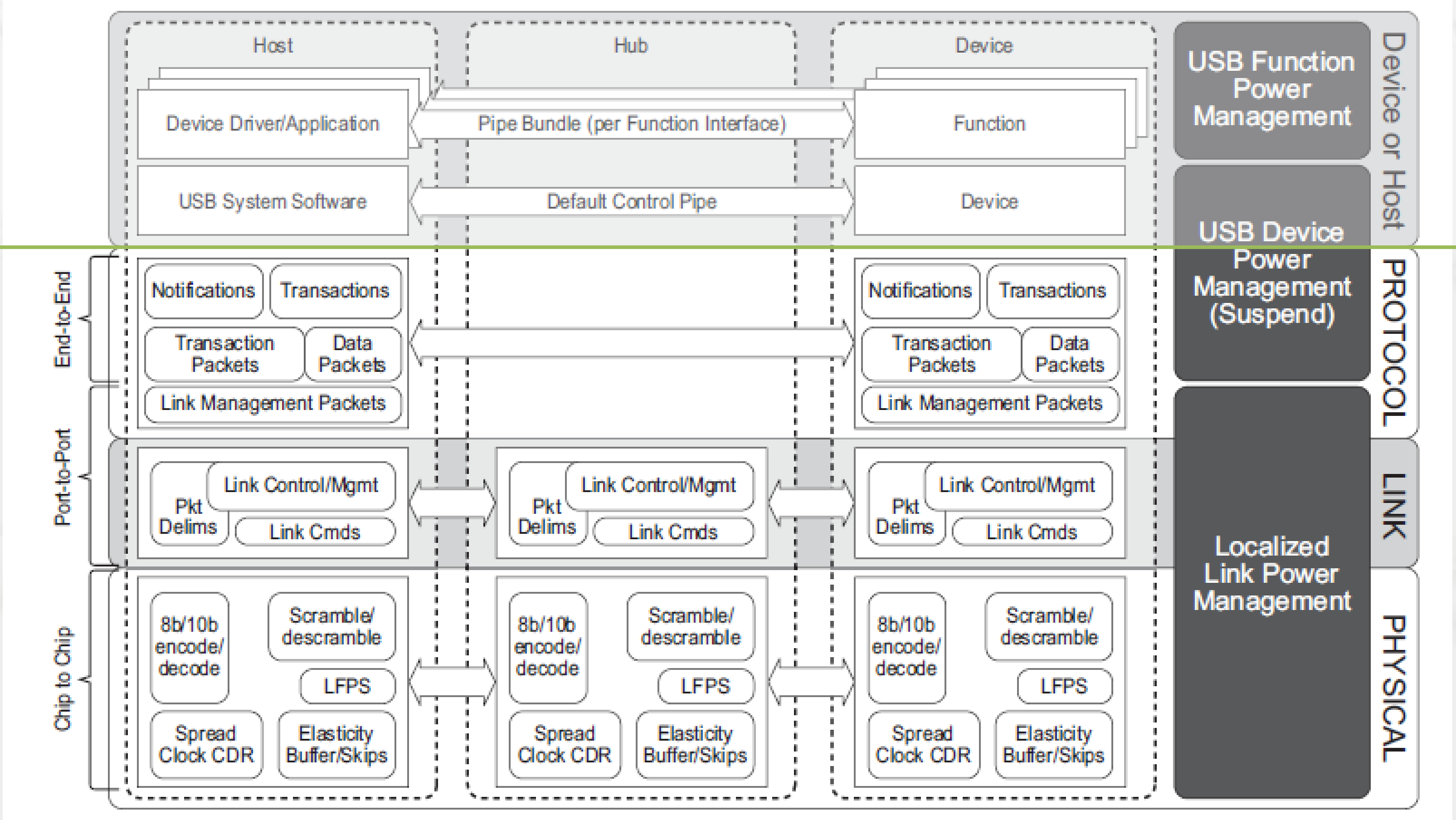
- Standard-B: Stationary peripherals
- Standard A: Same as USB 2.0 Standard-A, but with added pins for SS signals
- Micro-Connectors: for hand held devices

Layered Communication Architecture

- **USB 3.0 Specification defines 3 layers:**
  - Physical Layer (Chip-to-Chip)
  - Link Layer (Port-to-Port)
  - Protocol Layer (End-to-End)

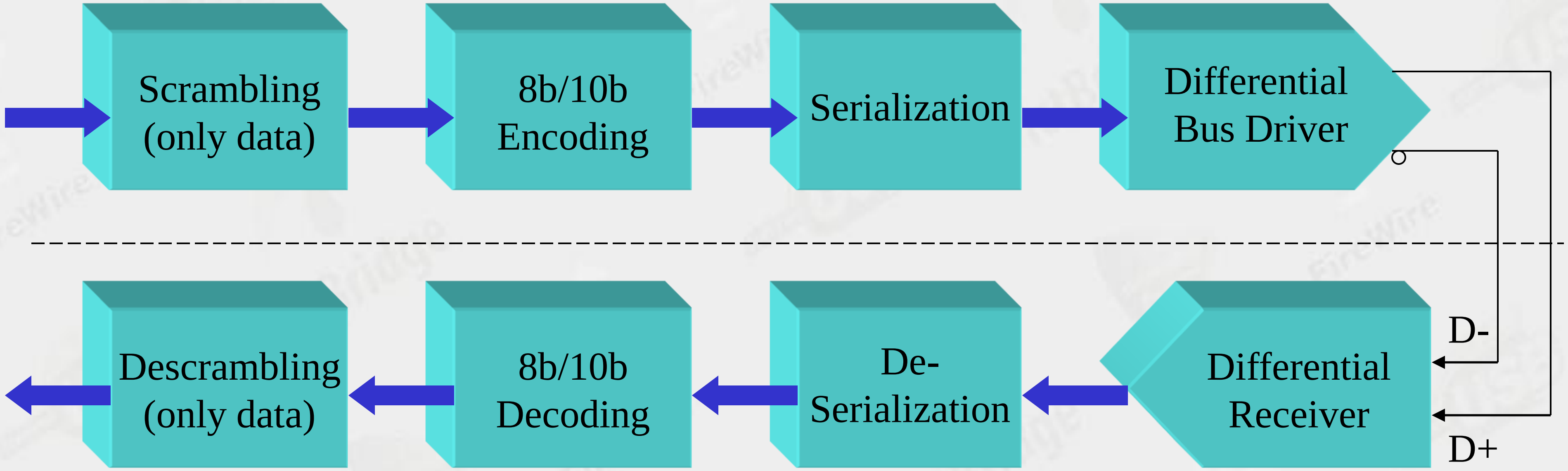
Layered Communication Architecture

- The big picture: This should be independent on USB 2.0 or USB 3.0



Physical Layer

Data Flow in Transmitter



Data Flow in Receiver

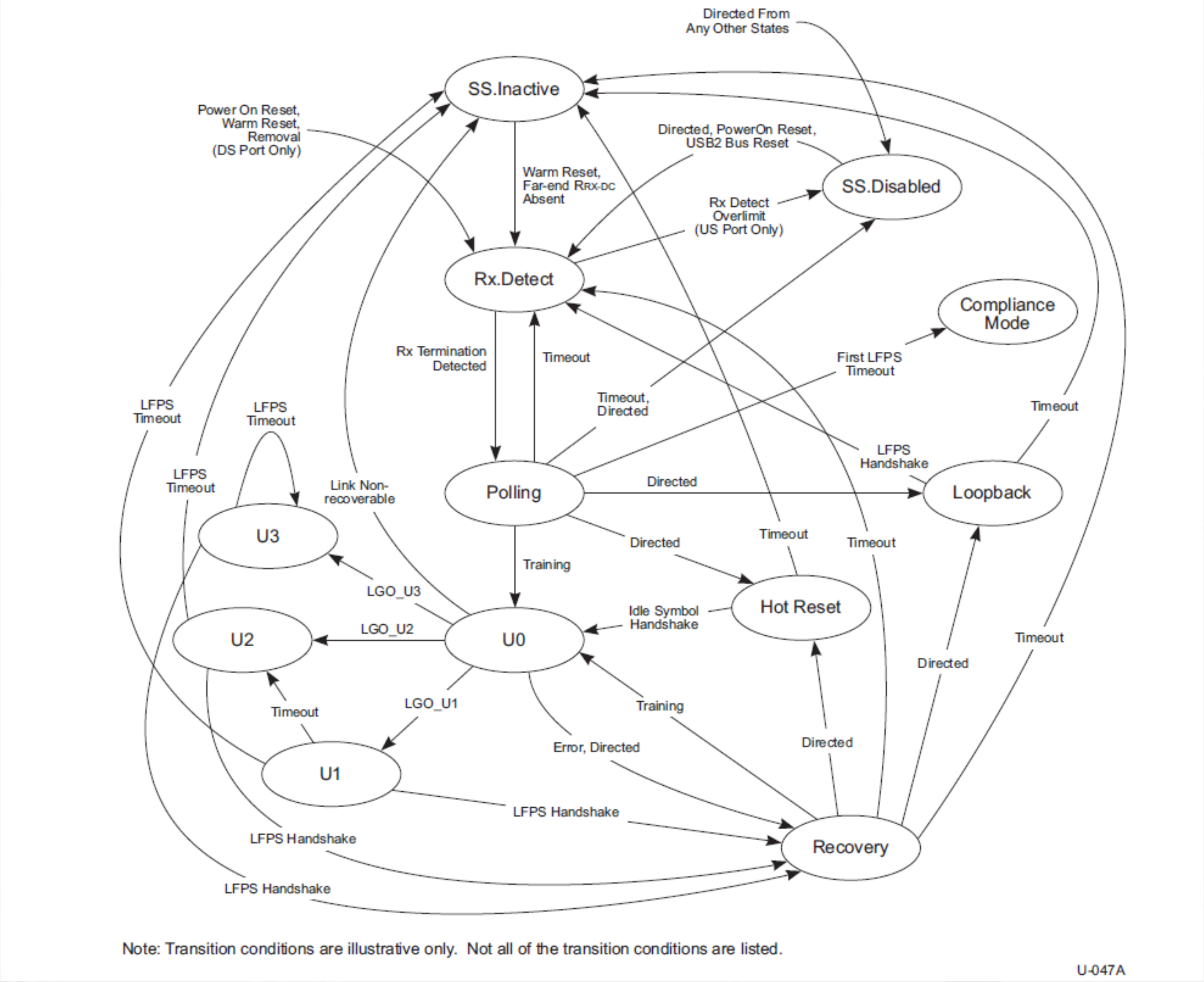
Physical Layer Tasks

- **Packet transmission across differential pairs**
  - Scrambling/Unscrambling to reduce EMI problems
  - 8/10b Encoding/Decoding: Bytes are converted from/to 10-bit Symbols (D-Symbols and K-Symbols)
  - Serialization and De-Serialization
- **Low Frequency Periodic Signaling during electrical idle state**
- **Clock and data recovery at receiver**

Link Layer

- Link Training and Status State Machine (LTSSM)
- Packet Framing
- Link command definition and usage
- Link power management
- Responsible for error handling, CRC protection, Recovery

LTSSM

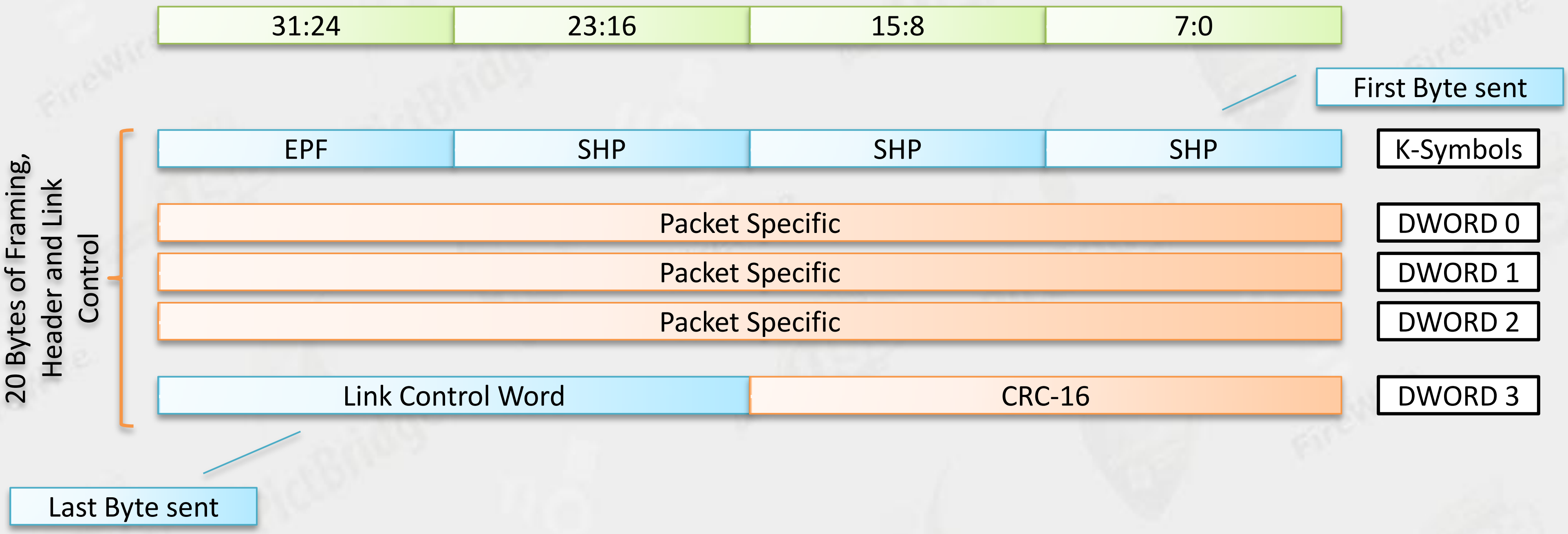


Note: Transition conditions are illustrative only. Not all of the transition conditions are listed.

Packet Framing

- **Link layer is responsible for the framing of all packet types (as defined at Protocol Layer)**
  - Link Management Packets (LMP)
  - Transaction Packets (TP)
  - Data Packets (DP)
  - Isochronous Timestamp Packets (ITP)

Header Packet Framing



31:24	23:16	15:8	7:0	
EPF	SHP	SHP	SHP	K-Symbols
Packet Specific				DWORD 0
Packet Specific				DWORD 1
Packet Specific				DWORD 2
Link Control Word		CRC-16		DWORD 3

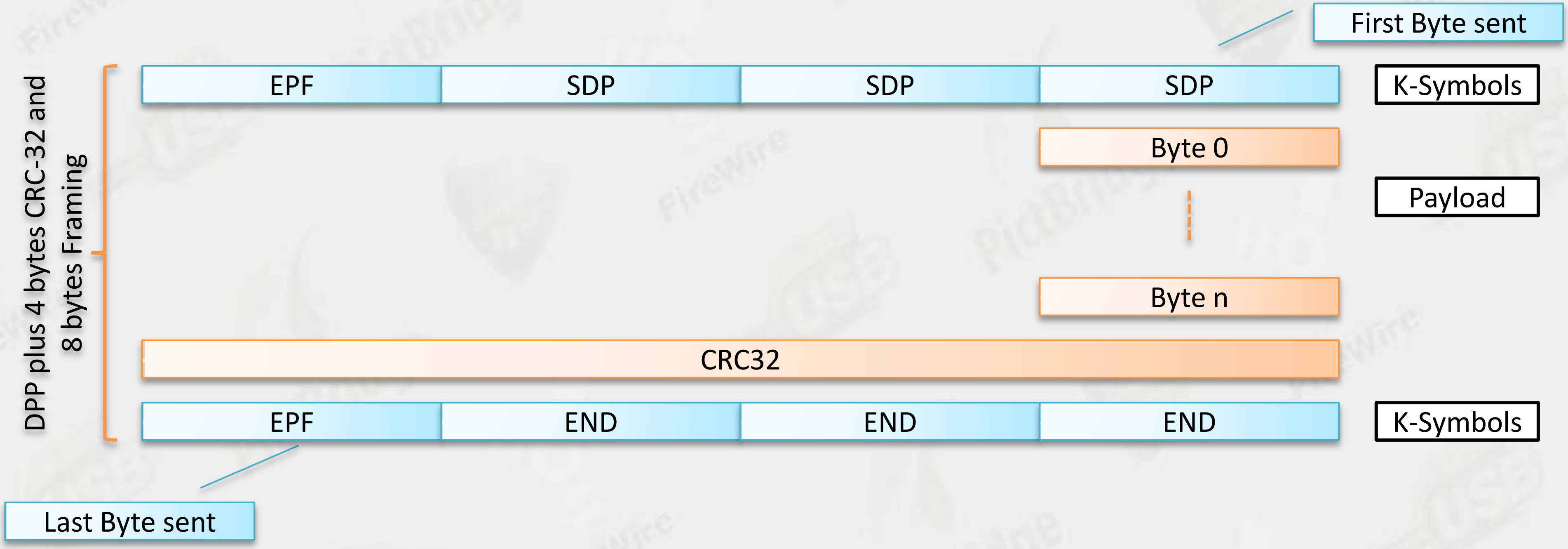
First Byte sent

Last Byte sent

20 Bytes of Framing, Header and Link Control

- Used for LMP, TP, DP (Header) and ITP

Data Packet Payload Framing

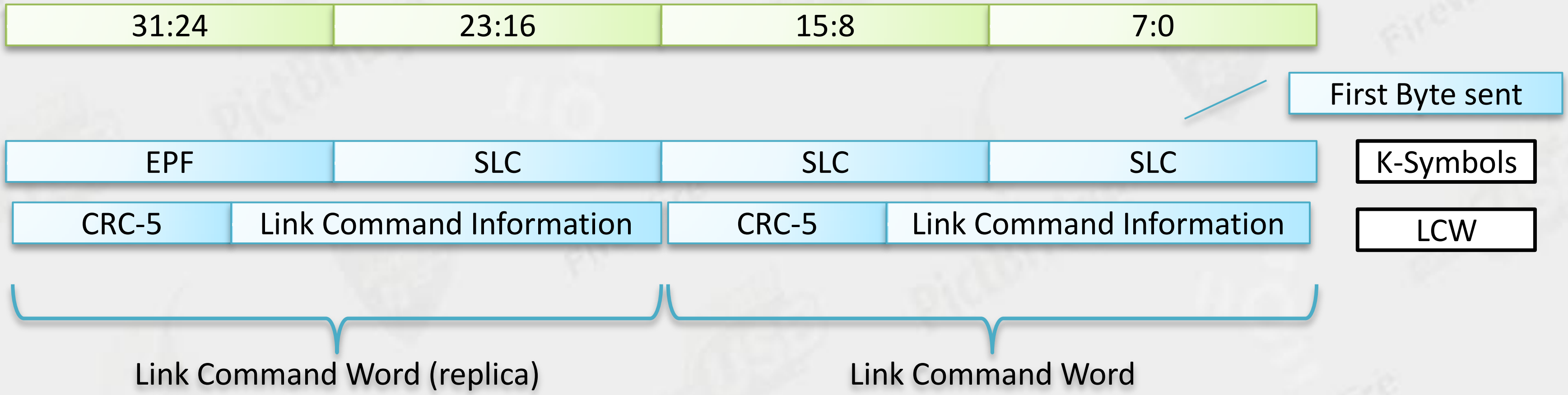


- Used for DP (Payload) only

Link Commands

- **Used for four use-cases:**
  - Ensure successful transfer of packets
  - Link flow control
  - Link power management
  - Special link commands to signal presence in U0
- **Fixed length of 8 symbols**

Link Command Structure



31:24 | 23:16 | 15:8 | 7:0

First Byte sent

EPF | SLC | SLC | SLC — K-Symbols

CRC-5 | Link Command Information | CRC-5 | Link Command Information — LCW

Link Command Word (replica)

Link Command Word

Link Command Summary

Class (LCW[10:9])	Type (LCW[8:7)]	Sub-Type (LCW[3:0])	Description
00b	00b: LGOOD_n	0000b..0111b: LGOOD_0 .. LGOOD_7	Indicates successful header packet reception. (ensure HP data integrity)
	01b: LCRD_x	0000b..0011b: LCRD_A .. LCRD_D	Signal availability of Rx Header buffers. (HP flow control)
	10b: LRTY		Header packet re-sent.
	11b: LBAD		Indicates failed header packet reception.
01b	00b: LGO_Ux	0001b..0011b: LGO_U1 .. LGO_U3	Link Power Management
	01b: LAU		
	10b: LXU		
	11b: LPMA		
10b	00b: LUP		Indicate Port presence in U0
	11b: LDN		
11b			Reserved

Link Power Management

- **USB 3.0 defines a much more complex and efficent power management concept**
- **4 power states U0..U3 instead of having 2 power states for USB 2.0 (Active and Suspend)**
  - U0: Fully powered
  - U1: low-power mode with fast recovery time (several us)
  - U2: low-power mode with slow recovery time (up to some ms)
  - U3: low-power mode with greatest power saving but slowest recovery time

Link Power Management

- **Transition to U1/U2 is managed by hardware**
- **Software can only “allow” the transition to U1/U2**
  - Dedicated USB Requests to enable/disable transition to U1/U2
- **Transition to U2 is under software control**
- **USB 3.0 devices working in non-SS mode must support the legacy LPM protocol**

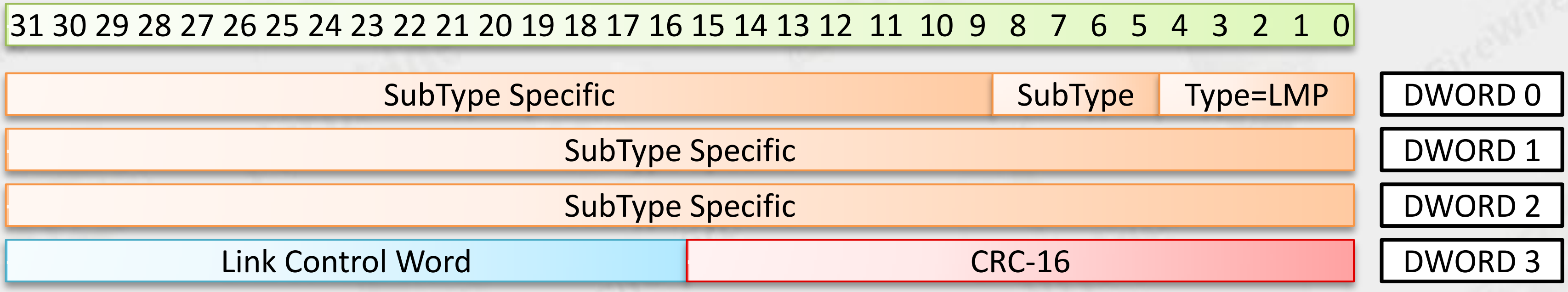
Protocol Layer

- Manages end-to-end data flow between device and host
- Defines packet types and formats (LMP, TP, DP, ITP)
- Describes flow-control and expected responses
- Supports same 4 transfer types as defined for USB 2.0
  - Adds stream support for bulk transfer type
- Error handling, CRC protection, Recovery

Link Management Packet

- **Only transferred between a pair of links**
- **Managing the link**
  - No addressing information, not routable
  - Port Capability exchange and port configuration
  - Power management optimization
  - Vendor specific device testing

Link Management Packet



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

SubType Specific | SubType | Type=LMP — DWORD 0

SubType Specific — DWORD 1

SubType Specific — DWORD 2

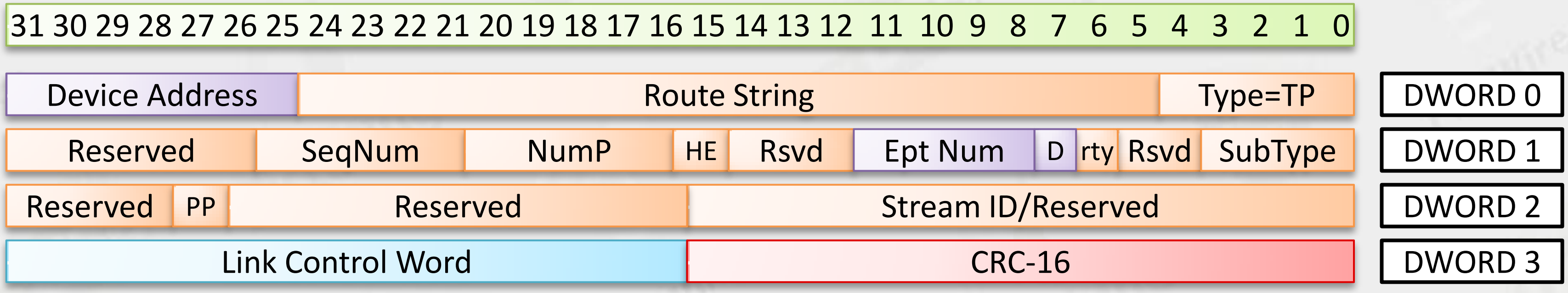
Link Control Word | CRC-16 — DWORD 3

SubType	Type of LMP
0000b	Reserved
0001b	SetLinkFunction
0010b	U2 Inactivity Timeout
0011b	Vendor Device Test
0100b	Port Capability
0101b	Port Configuration
0110b	Port Configuration Response
0111b-1111b	Reserved

Transaction Packet

- Used to control the data flow and manage the end-to-end connection
- Contains routing information
- Contains "Addressing Triple"
  - Device Address
  - Endpoint Number
  - Direction Field

Transaction Packet



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Device Address | Route String | Type=TP — DWORD 0

Reserved | SeqNum | NumP | HE | Rsvd | Ept Num | D | rty | Rsvd | SubType — DWORD 1

Reserved | PP | Reserved | Stream ID/Reserved — DWORD 2

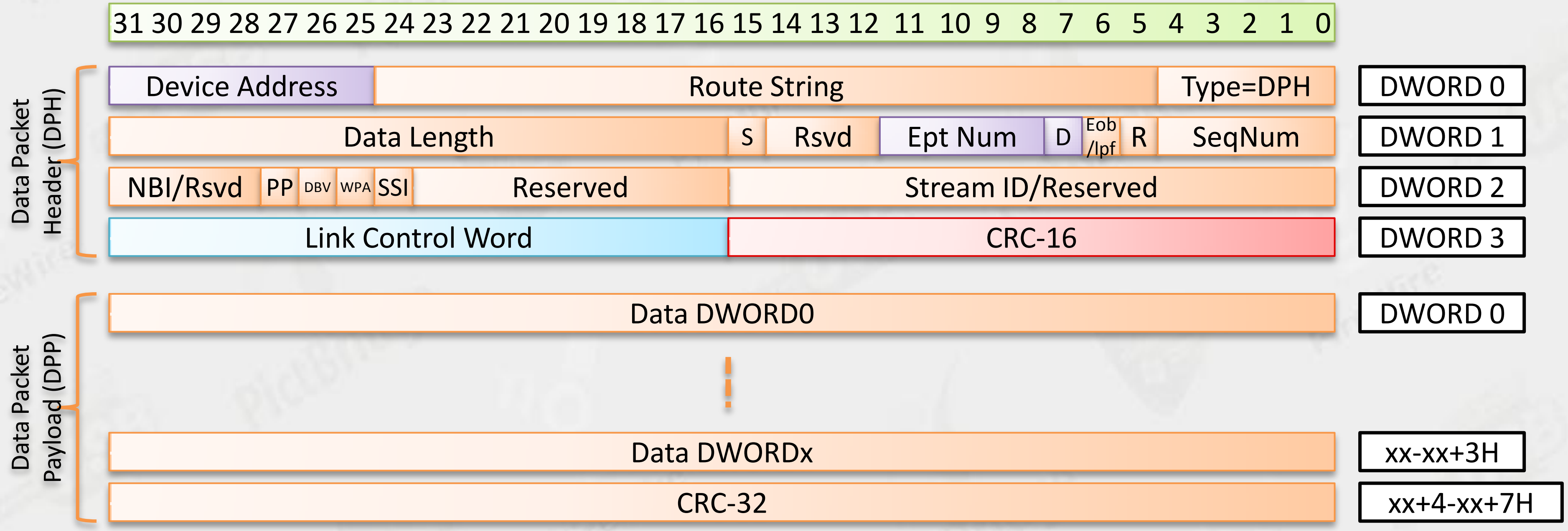
Link Control Word | CRC-16 — DWORD 3

SubType	Type of TP
0000b	Reserved
0001b	ACK
0010b	NRDY
0011b	ERDY
0100b	STATUS
0101b	STALL
0110b	DEV_NOTIFICATION
0111b	PING
1000b	PING_RESPONSE
1001b-1111b	Reserved

Data Packet

- Used to transfer data between Host and Device
- Consists of Data Packet Header (DPH) and Data Packet Payload (DPP)
- It’s permitted to send Data Packets with a zero length
- Contains Routing information and “Addressing Triple”

Data Packet



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

Data Packet Header (DPH)

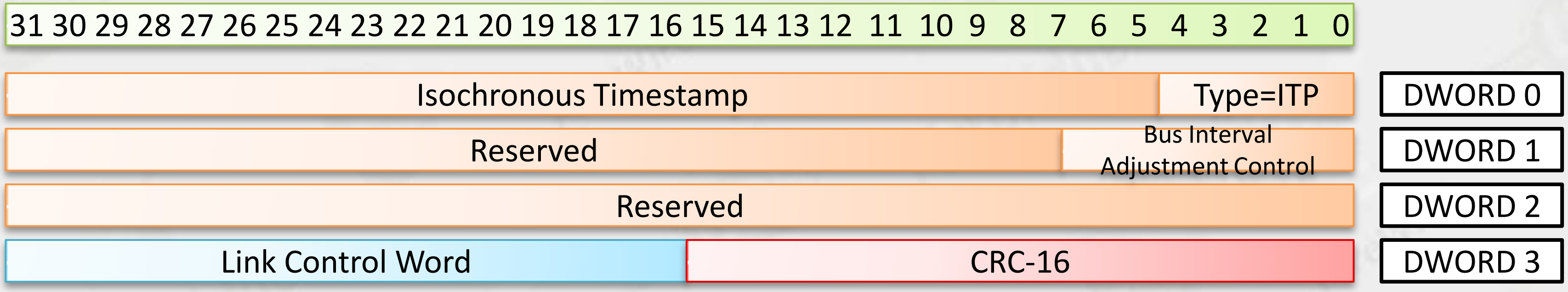
Fields	
Device Address | Route String | Type=DPH	DWORD 0
Data Length | S | Rsvd | Ept Num | D | Eob /lpf | R | SeqNum	DWORD 1
NBI/Rsvd | PP | DBV | WPA | SSI | Reserved | Stream ID/Reserved	DWORD 2
Link Control Word | CRC-16	DWORD 3

Data Packet Payload (DPP)

Fields	
Data DWORD0	DWORD 0
⋮	
Data DWORDx	xx-xx+3H
CRC-32	xx+4-xx+7H

Isochronous Timestamp Packet

- Multicast packet, no routing information
- Provide host timing information to devices for synchronization
- No response to ITPs



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

Isochronous Timestamp | Type=ITP | DWORD 0

Reserved | Bus Interval Adjustment Control | DWORD 1

Reserved | DWORD 2

Link Control Word | CRC-16 | DWORD 3

Packet Routing

- One of major differences compared to USB 2.0
- Allows links to stay longer in low power state
- USB device address is obsolete, but retained

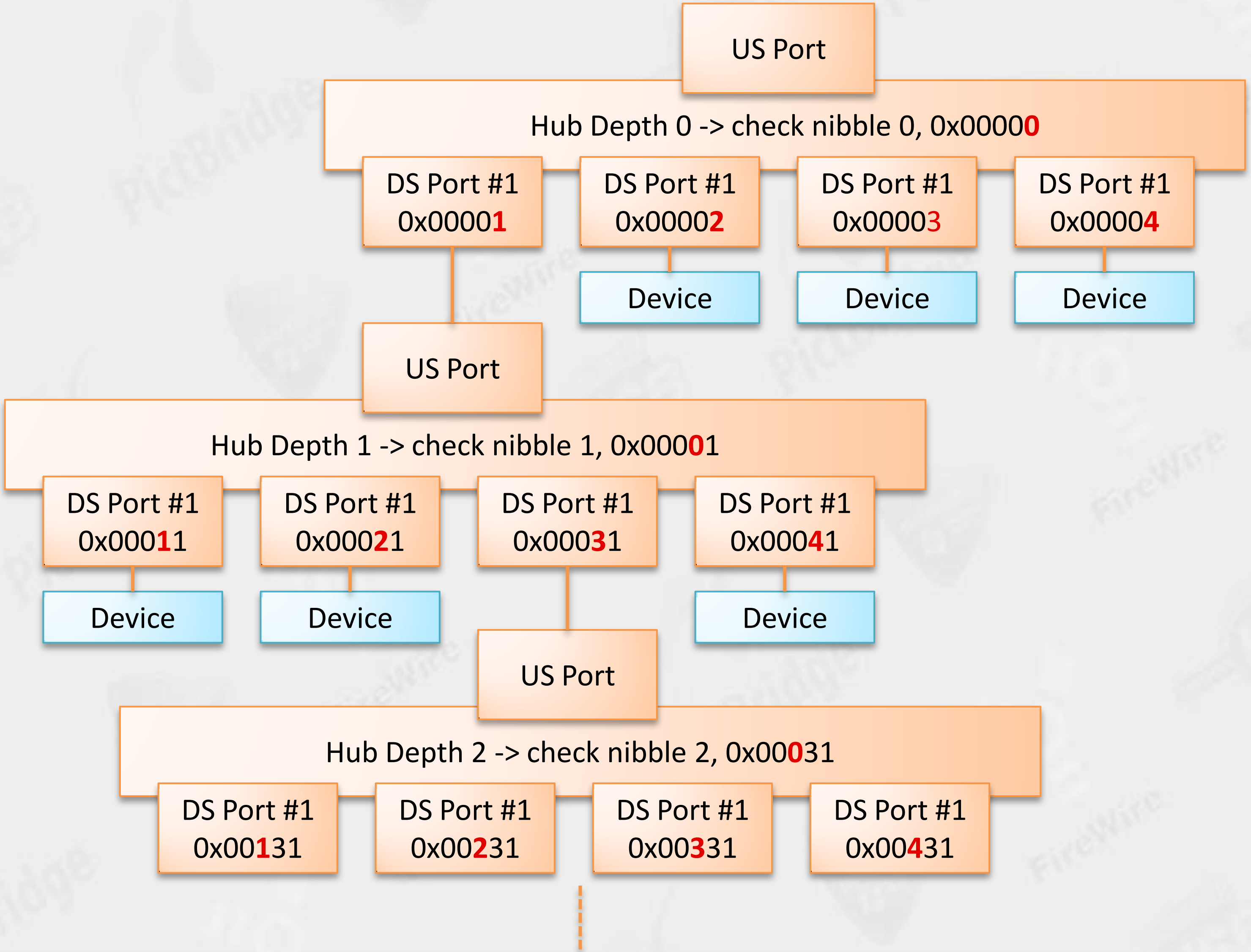
Packet Routing

19:16	15:12	11:8	7:4	3:0
Target Port Depth 4	Target Port Depth 3	Target Port Depth 2	Target Port Depth 1	Target Port Depth 0

Route String

- The hubs depth parameter is set by the host via a dedicated USB request
- Hubs ignore route string until they are in configured state
- If route string is zero, the packet is routed to the hub itself. Otherwise to a downstream port

Packet Routing Example

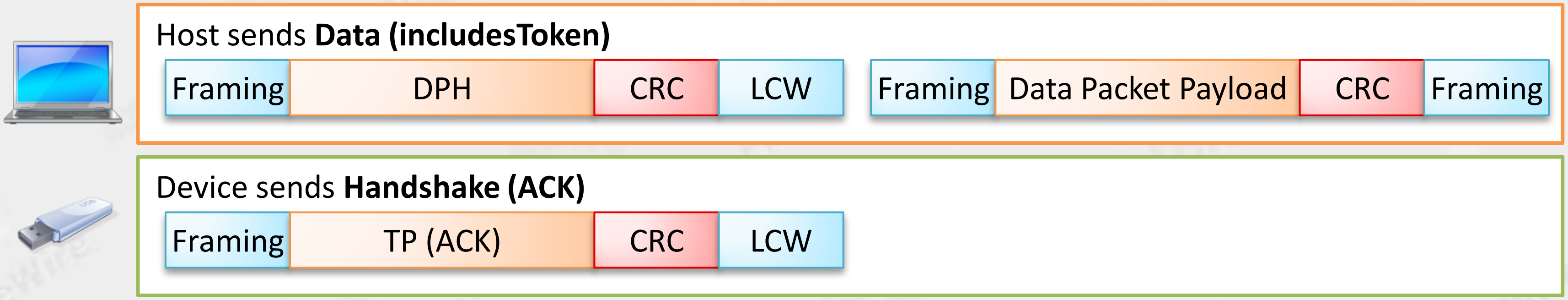


Transfer Types

Transfer-Type	Maximum Packet Size(Bytes)	Error Correction	Guaranteed Bandwidth	Burst	Usage
Control	LS: 8 FS: 8, 16, 32, 64 HS: 64 SS: 512	Yes	LS: 10% FS: 10% HS: 10% SS: -	1	Enumeration/Configuration (Requests, Descriptor-Data)
Interrupt	LS: 1 … 8 FS: 1 … 64 HS: 1 … 3073 [A] SS: 1 … 1024 [B]	Yes	LS: 90% FS: 90% HS: 90% SS: 80%	3	Usually used for small amount of data. (Mouse, Keyboard, Status-Information, …)
Isochronous	FS: 1 … 1023 HS: 1 … 3072 [A] SS: 0 … 1024 [B]	No	FS: 90% HS: 90% SS: 80%	1 … 16 [C]	Real-Time data (Audio, Video, …)
Bulk	FS: 8, 16, 32, 64 HS: 512 SS: 1024	Yes	-	1 … 16	Large amount of data. (Mass storage, printer, scanner…)

Simple OUT/IN Data Flow

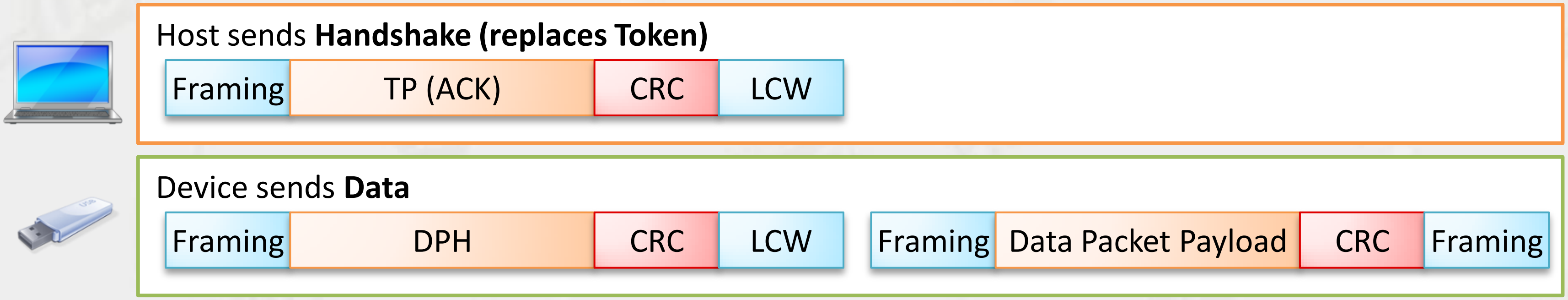
- OUT (Data transfer Host → Device)



Host sends **Data (includesToken)**

Device sends **Handshake (ACK)**

- IN (Data transfer Device → Host)



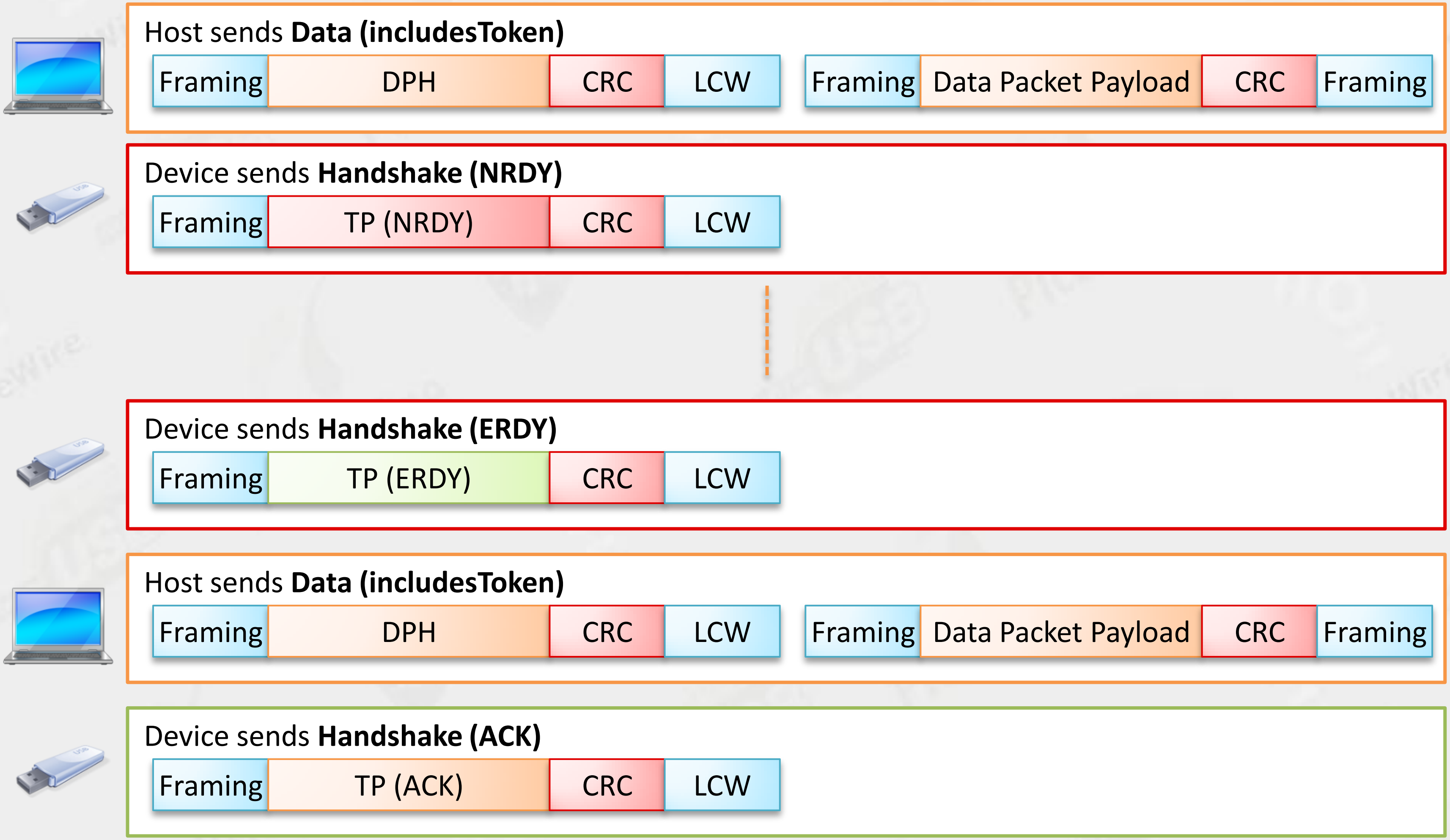
Host sends **Handshake (replaces Token)**

Device sends **Data**

Flow Control

- **Synchronization between TPs and DPs done via Sequence Number (SeqNum)**
- **ACK TP for IN transfers can have 2 semantics**
  - ACK the transfer as indicated by SeqNum
  - Act as “Token” to initiate a new transfer as indicated by NumP
- **ACK TP with “rty” set indicates that the packet must be retried**
- **NRDY and ERDY TPs are used to avoid polling**
- **STALL TP is used to indicate USB Stall condition**

OUT Data Flow Control



Host sends **Data (includesToken)**

Framing | DPH | CRC | LCW   Framing | Data Packet Payload | CRC | Framing

Device sends **Handshake (NRDY)**

Framing | TP (NRDY) | CRC | LCW

Device sends **Handshake (ERDY)**

Framing | TP (ERDY) | CRC | LCW

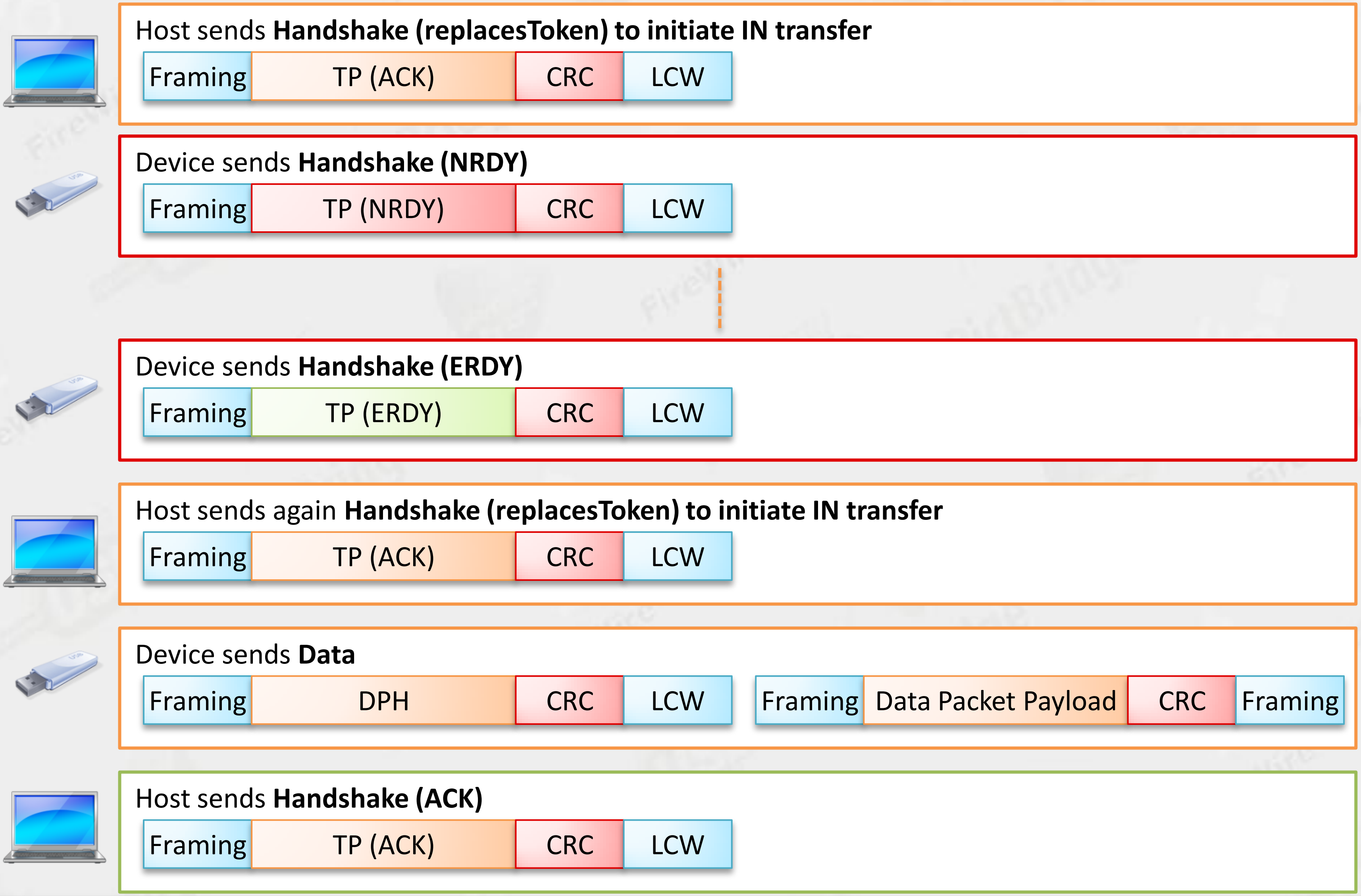
Host sends **Data (includesToken)**

Framing | DPH | CRC | LCW   Framing | Data Packet Payload | CRC | Framing

Device sends **Handshake (ACK)**

Framing | TP (ACK) | CRC | LCW

IN Data Flow Control



Host sends **Handshake (replacesToken) to initiate IN transfer**

Framing	TP (ACK)	CRC	LCW

Device sends **Handshake (NRDY)**

Framing	TP (NRDY)	CRC	LCW

Device sends **Handshake (ERDY)**

Framing	TP (ERDY)	CRC	LCW

Host sends again **Handshake (replacesToken) to initiate IN transfer**

Framing	TP (ACK)	CRC	LCW

Device sends **Data**

Framing	DPH	CRC	LCW	Framing	Data Packet Payload	CRC	Framing

Host sends **Handshake (ACK)**

Framing	TP (ACK)	CRC	LCW

Burst Transfers

- USB 3.0 allows the transfer of multiple data packets without waiting for an ACK
- Supported device burst size reported in Endpoint Descriptor
- All packets within a burst except the last packet must have the Maximum Packet Size
- NumP value of TP indicates the number of packets within a burst packets
- Each packet must still be ACK’d, NumP decremented with every ACK’d packet
- Device can end burst earlier by setting the “EOB” flag in the Data Packet Header

Sample Burst IN Data Flow

Host sends **Handshake (replaces Token) for first burst (4 packets)**

Framing	TP (ACK, Seq=0,NumP=4)	CRC	LCW

Device sends **Data**

Framing	DPH (Seq=0)	CRC	LCW	Framing	Data Packet Payload	CRC	Framing

Device sends **Data**

Framing	DPH (Seq=1)	CRC	LCW	Framing	Data Packet Payload	CRC	Framing

Device sends **Data**

Framing	DPH (Seq=2)	CRC	LCW	Framing	Data Packet Payload	CRC	Framing

Device sends **Data**

Framing	DPH (Seq=3)	CRC	LCW	Framing	Data Packet Payload	CRC	Framing

Host sends **Handshake for next burst**

Framing	TP (ACK, Seq=1,NumP=4)	CRC	LCW

Stream Protocol

- **USB 3.0 defines a new Stream Protocol for bulk transfers**
- **Multiplexing/De-multiplexing streams via one Endpoint**
- **Stream is identified via Stream ID (SID) in DP headers and in TPs for ACK, NRDY and ERDY**
    - 0x0000 is the reserved SID a standard bulk pipe
    - 16 bit value 0x0001..0xFFFD
    - 0xFFFE indicates “Prime” SID
    - 0xFFFF indicates “NoStream” SID

USB Device Framework

- Additional USB Requests
- Minor changes at descriptors

Device Descriptor

- USB 3.0 devices must report bcdUSB 0x300 in their device descriptor in SS mode, and 0x210 in non-SS mode
- bMaxPacketSize0 field must be set to 0x09 to indicate 512 byte packet size

Binary Object Store (BOS) Descriptor

- Framework to add device-level capabilities
- Number of “Device Capabilities” reported in Descriptor
- Additional DeviceCapabilies are added to this descriptor

BOS Device Capabilities

Capability Code	Value	Description
Wireless USB	0x01	Defines the set of Wireless USB-specific capabilities
USB 2.0 Extension	**0x02**	**USB 2.0 Extension Descriptor**
SuperSpeed_USB	**0x03**	**SS specific Capabilities**
CONTAINER_ID	0x04	Unique ID to identify the instance across all operating modes
Reserved	0x00, 0x05..0xFF	

USB 2.0 Extension

- Indicates extensions on top of USB 2.0 Standard
- Actually only the LPM feature can be reported using this descriptors
- Mandatory for USB 3.0 devices

SuperSpeed Device Capability

- **Explains device capabilities for SuperSpeed devices**
    - Latency Tolerance Message Capability (Power Management feature)
    - Supported Speeds
    - Lowest Speed at which all functionality is available to the user
    - U1/U2 Device Exit Latency (Power Management feature)

SuperSpeed Endpoint Companion Descriptor

- Each Endpoint Descriptor is followed by a SS Endpoint Companion Descriptor
- Contains additional endpoint characteristics for SS endpoints
  - MaxBurst
  - MaxStreams
  - Mult value for isochronous endpoints
  - wBytesPerInterval