Optical Data Interface ODI-1 Physical Layer Preliminary Specification

Revision 2, Date 180420

The ODI Specification is managed by the AXIe Consortium.
For more information about ODI, go to http://axiestandard.org/odispecifications.html
For more information about the AXIe Consortium, go to http://axiestandard.org

ODI 3-part Specification

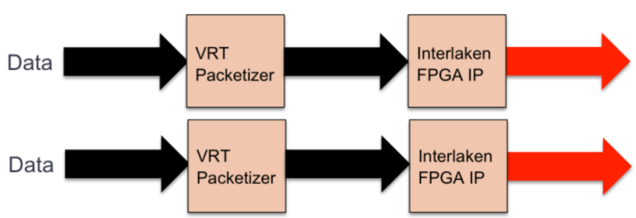
ODI-2.1: High-Speed Formats

- 8 to 16 bit data formats
- Packing Methods
- Optimized for SDR & 5G

. . .

Data Formats

ODI-2: Transport Layer



- VITA-49 “VRT” Packets
- FPGA Optimized
- Port Aggregation
- Context Packets

Transport Layer

ODI-1: Physical Layer

- 12 lane multimode optics
- 12.5 & 14.1 Gb/s
- Interlaken Protocol
- Flow Control

Physical Layer

ODI-1 Scope

- ODI-1 defines the physical layer of the Optical Data Interface (ODI) specification
- It includes
  - Optical ports
  - Optical cables
  - Optical bit rates and lane widths
  - Interlaken protocol use
  - Flow control
  - Packet framing and lengths
  - State diagrams for streaming
  - Documentation requirements

ODI-1 Compliance

- RULE: All implementations of of this specification SHALL comply with all the rules in this specification.
- RULE: All implementations of of this specification SHALL comply with all the requirements in the Interlaken Protocol Definition, Revision 1.2 or later.
- RECOMMENDATION: All implementations of of this specification SHOULD comply with all the recommendations in this specification.
- RULE: All implementations of of this specification SHALL clearly specify any and all deviations from the recommendations in this specification.
- RULE: All implementations of of this specification SHALL comply with the documentation requirements of this specification

Glossary - 1

- Device
  - An assembly that generates or receives data and has one or more optical ports
- Port
  - A single optical connector on a device, and the associated electronics
- Cable
  - A multiple fiber cable that connects between two ports
- Link
  - A unidirectional connection between two ports, consisting of 12 lanes of multimode optical transmission. A bi-directional connection has two links, one in each direction.
- Producer
  - ODI device that generates data to be sent over one or more optical ports
- Consumer
  - ODI device that receives data sent over one or more optical ports
- Transmitter
  - Interlaken term for a producer
- Receiver
  - Interlaken term for a consumer. VITA term for an RF receiving device.
- Emitter
  - VITA term for a producer.
- Exciter
  - VITA term for an RF signal generator

Glossary - 2

- Interlaken
  - Interlaken is the name of a chip-to-chip interface specification that is used by ODI to transfer packets between two ODI ports. It is the primary communication protocol. Separately, the packet structure sent over Interlaken is defined to be VRT, defined in the ODI-2 specifications.
- VRT
  - VRT is an abbreviation for VITA Radio Transport, standardized in VITA 49.2, and enhanced by other VITA 49x specifications. VRT specifies the structure and behavior of VRT packets, which carry data, context, and control information about signals, and the data stream itself. VITA 49 may be abbreviated as V49, as VITA 49.x may be abbreviated as V49.x
- Channel
  - "Channel" is used differently in Interlaken specifications than is commonly understood in operational or instrumentation systems as a signal channel.
  - Channel is used by Interlaken to enable a completely different data stream with its own flow control. ODI generally uses only a single Interlaken channel.
  - Channel is used by VRT similarly to instrumentation systems.
  - Synchronous instrumentation channels are encoded into the VRT stream in a rotating sequence, and are referred to as a "sample vector" in VRT parlance. VRT Sample Vector Size field is the number of instrumentation channels minus 1. This assumes synchronous channels, all at the same data rate and resolution.

Glossary - 3

- Word
  - An Interlaken Word is 8 bytes (64 bits)
  - A VRT Word is 4 bytes (32 bits)
- Burst
  - In Interlaken, data is divided into data bursts, each delineated by one or more burst control words.
- BurstMax
  - An Interlaken parameter that determines the maximum number of data bytes sent for each burst. Typically, streaming data will be set with these burst lengths. ODI allows 256 and 2048 byte BurstMax.
- BurstShort
  - An Interlaken parameter that reflects the shortest burst allowed.
- BurstMin
  - An Interlaken parameter for the Optional Scheduling Enhancement that guarantees all packets are at least BurstMin in length, and no idle control words will be needed for long packets.
- Packet
  - A packet refers to the block of data sent between Interlaken SOP and EOP (Start of Packet and End of Packet) indicators. At the Interlaken layer, the format of the packet is unknown. ODI-2 has defined the packet to be VRT packets. The term packet within ODI refers to both.

Glossary - 4

- Prologue
  - The Prologue refers to fields within a VRT data, context, or command packet that precede the data payload or context/command data payload respectively. A standard 28-byte Prologue is defined for each packet type.
- Trailer
  - The Trailer refers to the 4-byte field that follows the data payload within a VRT Data packet. There is no trailer associated with Context Packets or Command Packets.
- Processing-efficient packing
  - Processing-efficient packing refers to a data packing method within the VRT Packet data payload where the packed data is aligned to 32-bit boundaries.
- Link-efficient packing
  - Link-efficient packing refers to a data packing method within the VRT Packet data payload where the data is packed as tightly as possible, leading to the highest sample density and speed.

Glossary - 5

- Stream
  - A VRT term for a sequence of related packets. All packets of the same stream have the same Stream ID sent from the producer. A typical stream has consecutive Signal Data Packets, with optional Context Packets and/or Command Packets occasionally.
- Signal Data Packets
  - VRT term for a packet carrying digitized samples of one or more signals. This is the primary packet type of ODI. Most ODI systems will only include Signal Data Packets.
- Context Packet
  - VRT term for a packet carrying meta-data or "context" data related to the digitized signals in the same stream. This may include information such as reference level or sampling rate. Context Packets are optional in ODI, but a standard Context Packet is defined in ODI-2.1 if used.
- Command Packet
  - VRT term added in V49.2. Command Packets are used to control devices, and the control and acknowledgement process. The Control Packet is the only recommended Command Packet subtype, and has the same field types as the Context Packet, which are used for control. Control and other Command Packets are optional in ODI, but a standard Control Packet is defined in ODI-2.1 if used.

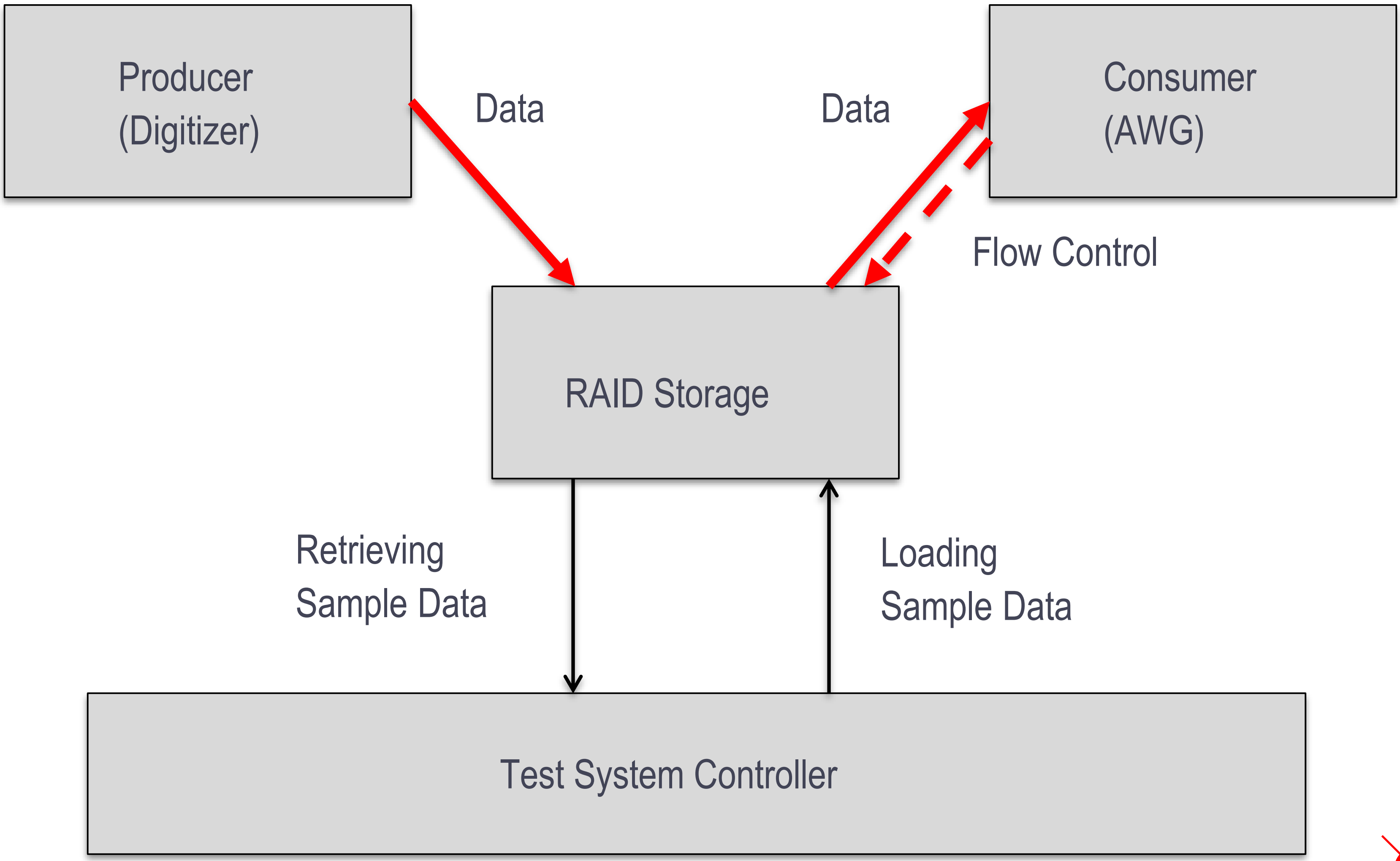
Glossary - 6

- Extension Packet
  - Extension Signal, Context, and Command packets are used when it is impossible to use the pre-defined data types. An example may be the sending of encrypted data.
- Train
  - For streaming applications, the Train refers to a series of packets, typically of the same size, sent sequentially from a producer, but not including the final packet, called the Caboose
- Caboose
  - For streaming applications, the Caboose refers to the final packet sent from the producer. It may or may not be the same size as the Train packets.
- Sample Vector
  - A Sample Vector is defined within V49.2 as a collection of synchronous Data Samples. This is the common method of transporting multi-channel sample data within the VRT data payload fields. Vector size describes the number of channels. However, the VRT Vector Size Field, used in V49.2 and ODI-2.1, is calculated as the vector size minus one. Therefore a two-channel stream has a vector size of two, but a Vector Size Field of 1.

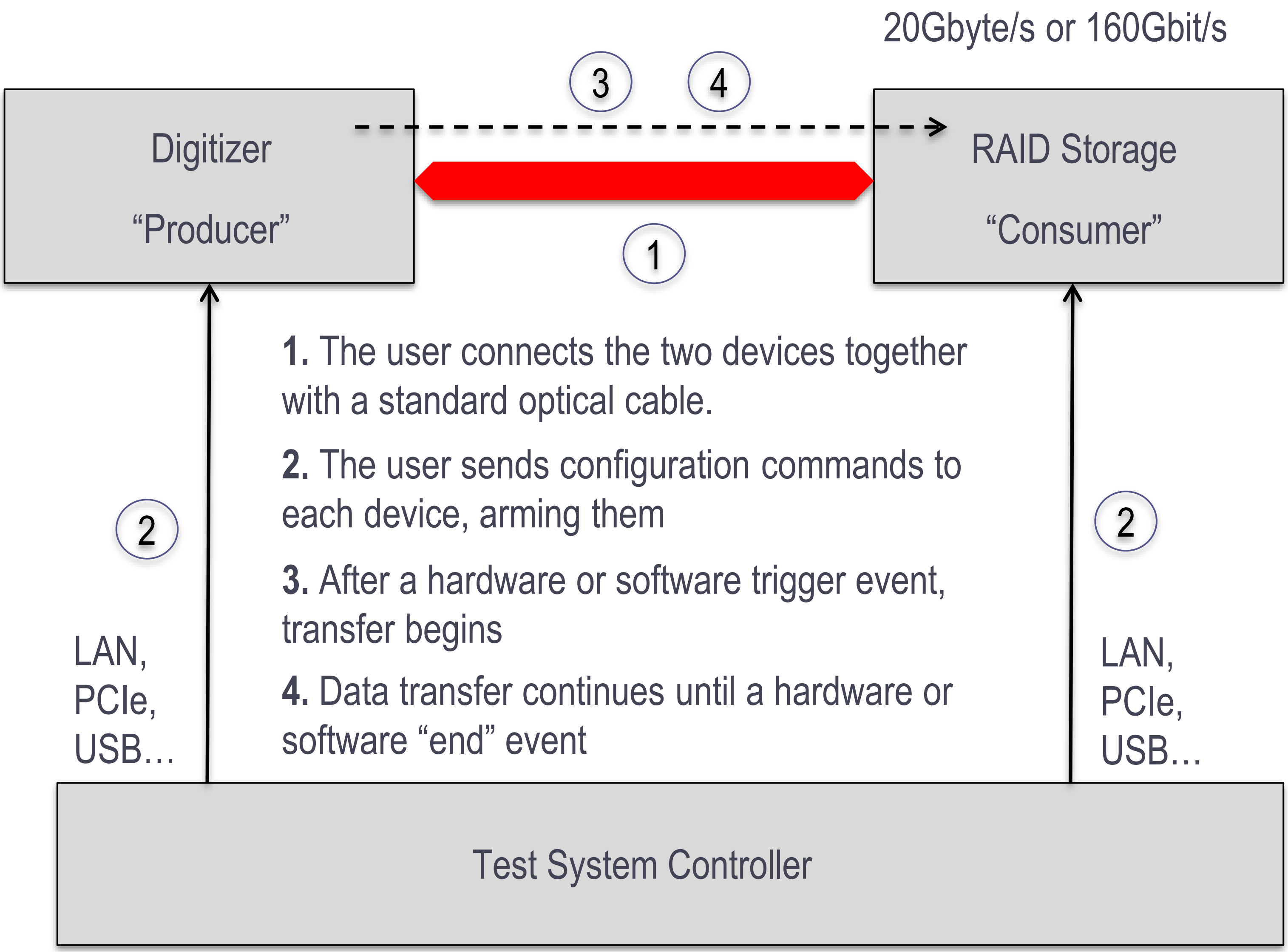
ODI-1 What is it?

- ODI-1 specifies the physical layer of a single optical interconnect for very high speed streaming applications between instruments, processors, and storage. It includes two line rates, one at 12.5Gb/s, and one at 14.1Gb/s. The latter allows 20GBytes/s continuous streaming from a single port.
- ODI-1 specifies the mechanical, optical, and timing requirements for each optical port. ODI ports may be deployed onto any electrical product; there is no requirement for any specific format (e.g. PXI, AXIe, LXI), or to be an instrumentation product at all. ODI-1 also specifies the mechanical and optical characteristics of the optical cable. In general, optical ports are either uni-directional or bi-directional optical links of 12 lanes. Optical cables are 24 lanes, 12 lanes in each direction.
- ODI-1 uses the Interlaken protocol to transfer data from a producer to a consumer. The Interlaken protocol sends arbitrary data over the link, separated into packets. ODI-1 does not specify the formats of the packets, though ODI-2 and ODI-2.1 specify VRT (VITA Radio Transport, also known as VITA 49.2) as the packet format.
- ODI-1 supports data streaming only (data plane). Commands are sent via the standard instrument and device interfaces. This does not preclude the use of VRT Command Packets.
- ODI-1 supports flow control, where a consumer can modulate the speed of the incoming data.
- ODI-2 adds multi-port transfers and generic VRT packet requirements.
- ODI-2.1 adds specific requirements for sending 8-bit to 16-bit sample data, and other data formats.

Operation: Data Plane, single port



Example operation: Storage



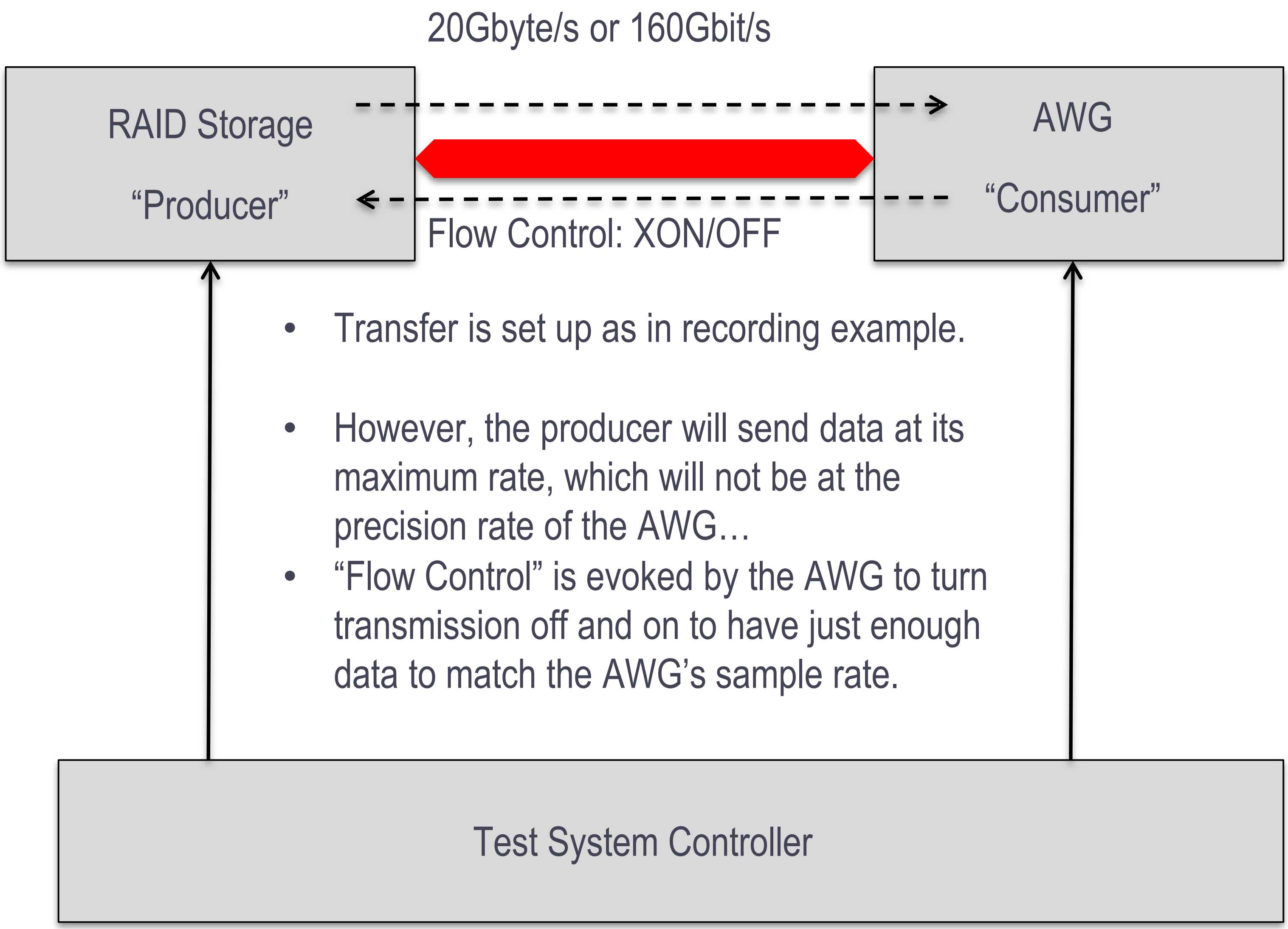
1. The user connects the two devices together with a standard optical cable.

2. The user sends configuration commands to each device, arming them

3. After a hardware or software trigger event, transfer begins

4. Data transfer continues until a hardware or software "end" event

Example 2: Playback of recorded or computed data



- Transfer is set up as in recording example.
- However, the producer will send data at its maximum rate, which will not be at the precision rate of the AWG…
- "Flow Control" is evoked by the AWG to turn transmission off and on to have just enough data to match the AWG's sample rate.

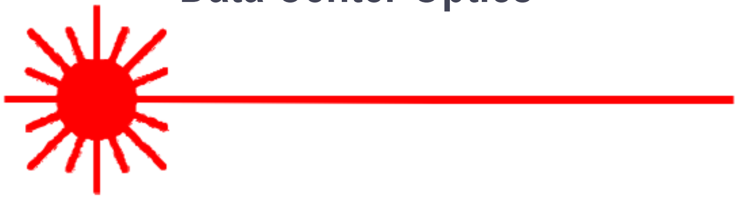
ODI-1 Layers

Interlaken Interconnect Protocol

- Packet Framing
- Flow Control
- SerDes Management
- FPGA independent

Protocol Layer

Data Center Optics

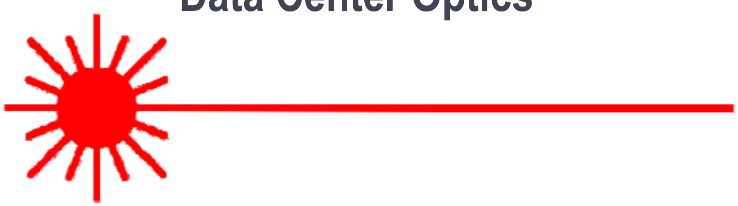


- 850nm VCSEL
- Multimode fiber
- 12 Tx & 12 Rx lanes
- 12.5Gb/s & 14.1Gb/s

Optical Layer

ODI-1 Optical Layer

Data Center Optics



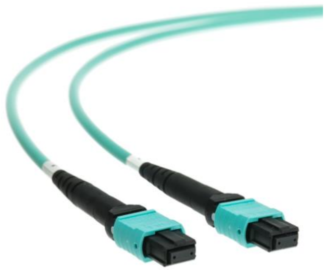
- 850nm VCSEL
- Multimode fiber
- 12 Tx & 12 Rx lanes
- 12.5Gb/s & 14.1Gb/s

Optical Layer

Safety

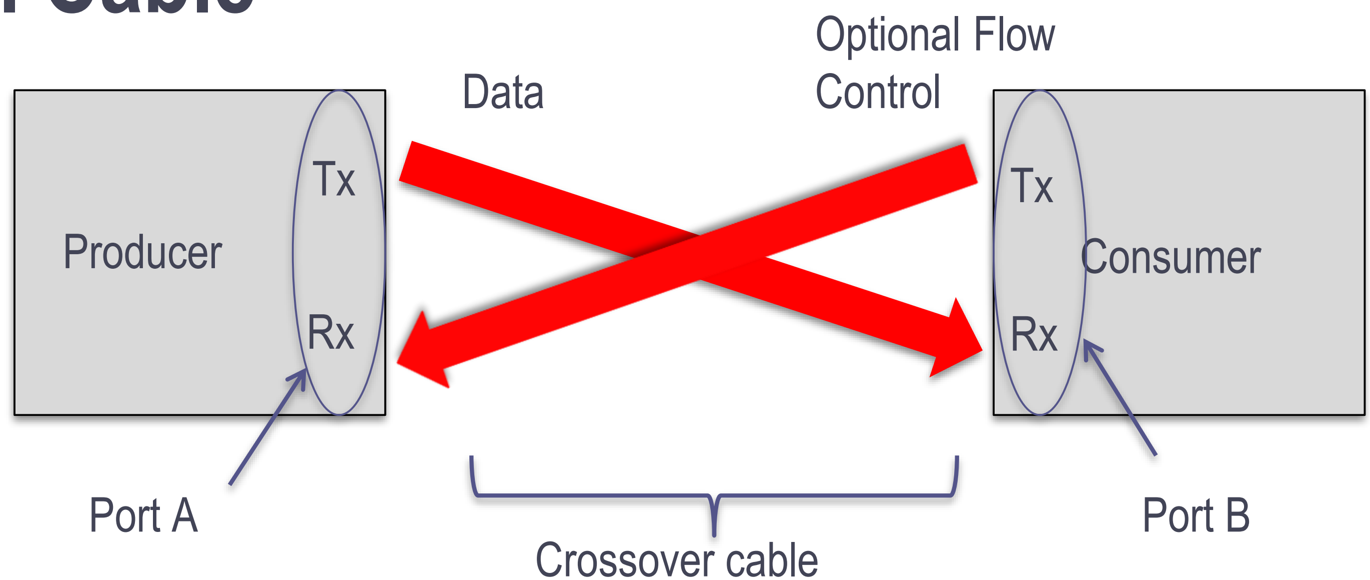
- RULE: Any ODI device SHALL be class 1 compliant to IEC EN 60825-1:2007.
- OBSERVATION: This is the strictest safety category, indicating no hazard during normal use.

ODI Optical Cable



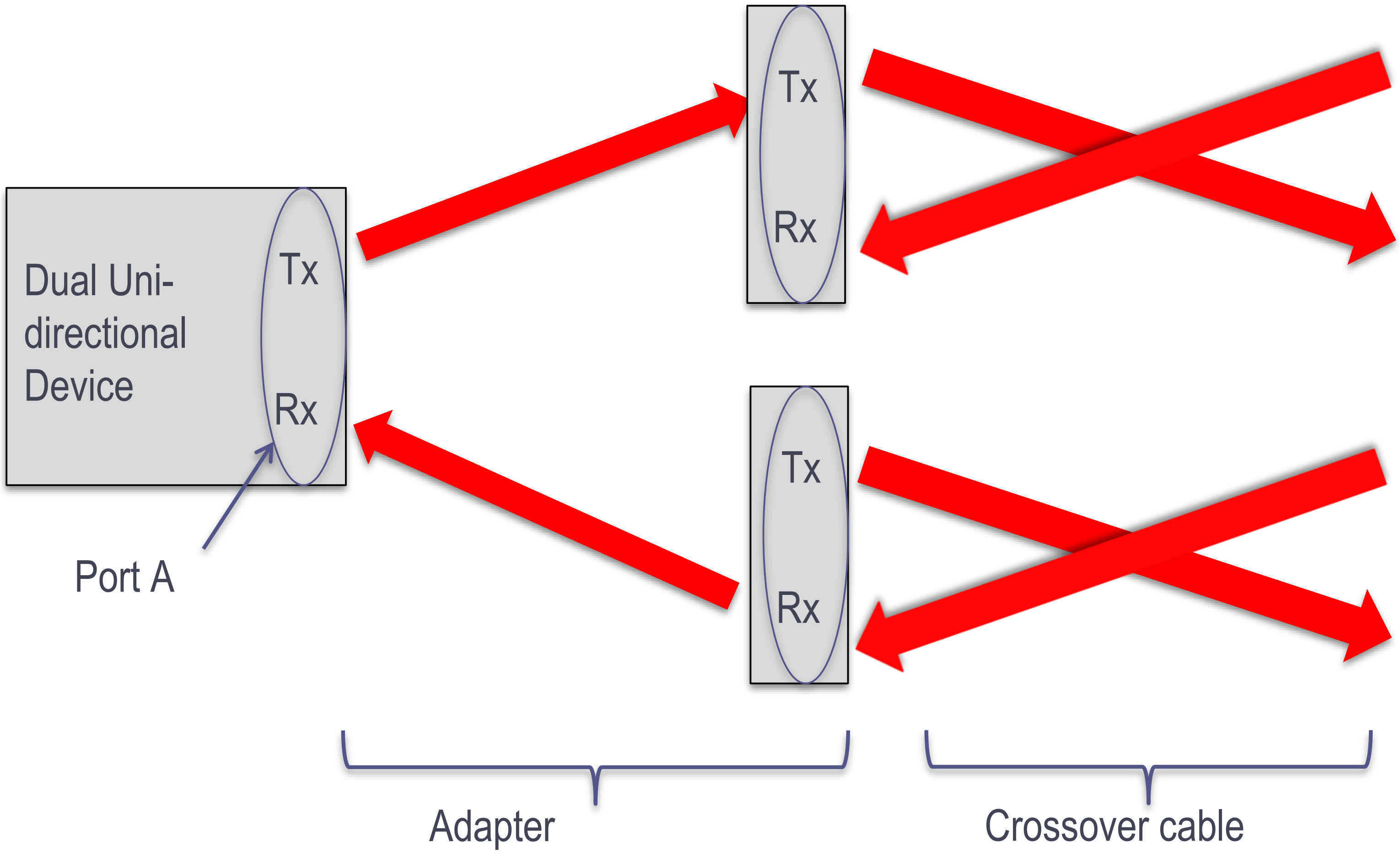
- A single bi-directional multiple fiber cable for all optical links
- 24 lanes: 12 lanes in each direction, crossover configuration
- OM3 850nm multimode fiber with MPO/MTP female connectors
- 14.1Gb/s on each lane enables 20GB/s in each direction
- Non-directional: Either end may be plugged into any device
- Cable is capable of higher speeds as optical Tx/Rx rates increase
- Up to 100 meters in length

Optical Cable



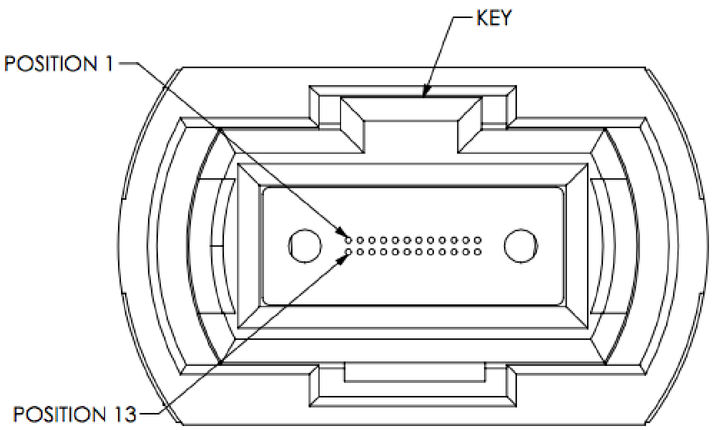
- RULE: An ODI-1 optical cable SHALL implement 12 lanes of multi-mode fiber in each direction, in a “crossover” configuration.
- RULE: An ODI-1 cable SHALL use an MPO style connector
- RULE: An ODI-1 cable SHALL NOT include the two ferrule guide pins
- RULE: Cable length SHALL NOT exceed 100m in length
- PERMISSION: A device MAY implement a “dual uni-directional port”, where the Tx and Rx connect to different devices.
- PERMISSION: A port may be configured through software to act either as a bi-directional port or as a dual uni-directional port

Optical Cable Adapter for dual uni-directional devices



Cable Pin Assignments

RULE: All ODI-1 cables SHALL follow the definitions below.



24 FIBER CONNECTOR

- All optical cables are 24 lanes, 12 lanes in each direction.
- All optical cables are configured in crossover topology, as indicated in pin assignment diagram to the right.
- ODI-1 cables SHALL NOT include the MPO Bulkhead adapter at either end.

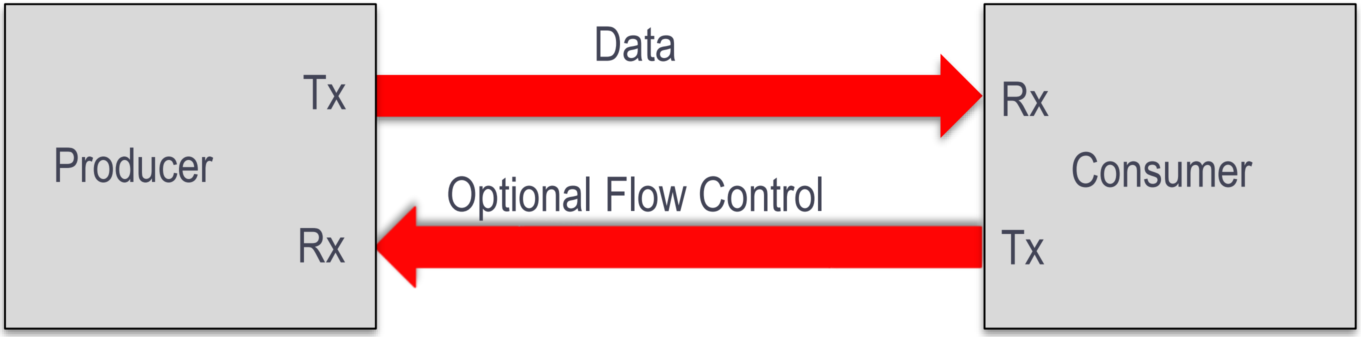
ODI-1 Cable Pin Assignments

SIDE A POSITION	FIBER COLOR		SIDE B POSITION
1	BLUE		13
2	ORANGE		14
3	GREEN		15
4	BROWN		16
5	SLATE		17
6	WHITE		18
7	RED		19
8	BLACK		20
9	YELLOW		21
10	VIOLET		22
11	ROSE		23
12	AQUA		24
13	BLUE	+	1
14	ORANGE	+	2
15	GREEN	+	3
16	BROWN	+	4
17	SLATE	+	5
18	WHITE	+	6
19	RED	+	7
20	BLACK	+	8
21	YELLOW	+	9
22	VIOLET	+	10
23	ROSE	+	11
24	AQUA	+	12

Optical Ports and Placement

- Optical connectors MAY be placed on the faceplate of a module or on any area of a traditional instrument or other product. This is referred to as a port.
- A bulkhead is placed around an ODI device's port to enable push on connection to an optical cable
- Allowable faceplate connectors are:
  - MPO connector (Multi-fiber Push On)
  - MTP is a US Conec brand name of MPO connectors built to tighter tolerances, and MAY be used.
- RULE: A ODI-1 device SHALL use MPO style connectors with two rows of 12 fibers each.
- PERMISSION: It is permissible to place a higher density connector on a product for density reasons, if the vendor also has an adapter to expand to multiple standard connectors.

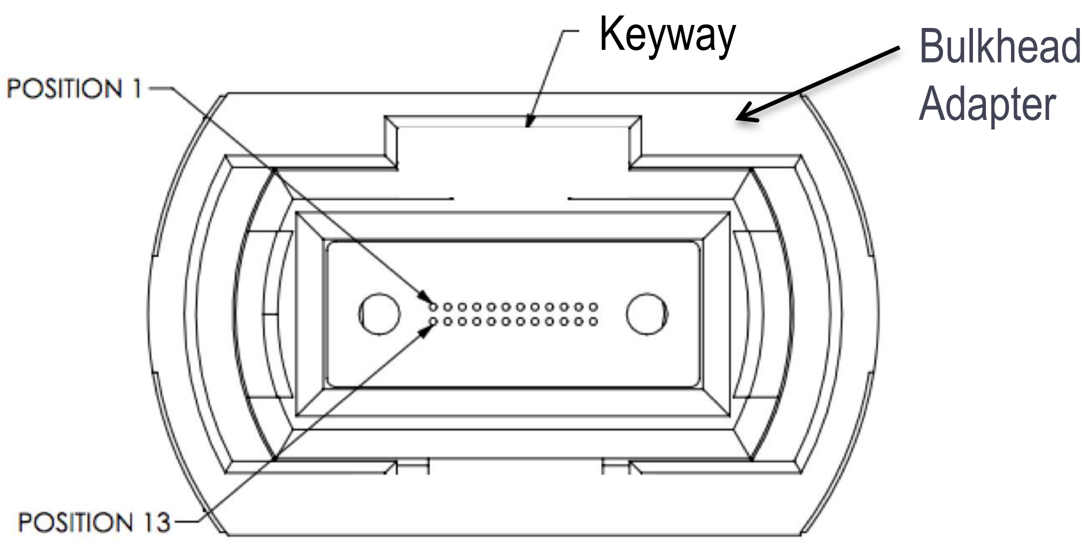
Ports



- RULE: An ODI-1 port SHALL include the two ferrule guide pins
- RULE: An ODI-1 port SHALL include a bulkhead connector for cable insertion
- RULE: A port SHALL implement either 12 lanes or 0 lanes in either direction. A port SHALL NOT implement more than 12 lanes in a single direction, nor between 1 and 11 lanes.
- OBSERVATION: A bi-directional port has 12 lanes in each direction, while a uni-directional port either transmits over 12 lanes, or receives over 12 lanes.
- OBSERVATION: To scale to larger than 12 fibers in each direction, additional ports are required.
- PERMISSION: A port MAY be configured as a dual uni-directional port. In this case, the Tx row and the Rx row are connected to different devices.

Port Pin Assignments

RULE: All ODI-1 ports SHALL follow the definitions below.



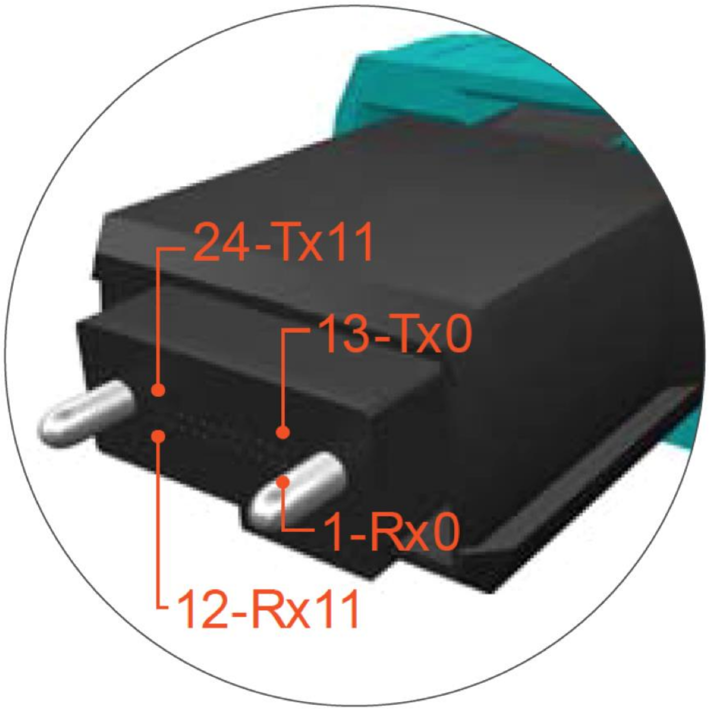
Front view of ODI port.

Function	MPO Port Position
Tx11	1
Tx10	2
Tx9	3
Tx8	4
Tx7	5
Tx6	6
Tx5	7
Tx4	8
Tx3	9
Tx2	10
Tx1	11
Tx0	12
Rx11	13
Rx10	14
Rx9	15
Rx8	16
Rx7	17
Rx6	18
Rx5	19
Rx4	20
Rx3	21
Rx2	22
Rx1	23
Rx0	24

- All ODI-1 ports SHALL include the MPO bulkhead adapter.
- All ODI-1 ports SHALL include the two ferrule guide pins
- All ODI-1 ports SHALL place the guide keyway adjacent to the row of transmitter pins
- OBSERVATION: The inclusion of the bulkhead adapter on the device allows ODI cables to be easily and reliably snapped in.

Port Pin Assignments - Implementation

PERMISSION: An ODI-1 port MAY internally follow the definition below, IF using an Opposed MPO Adapter

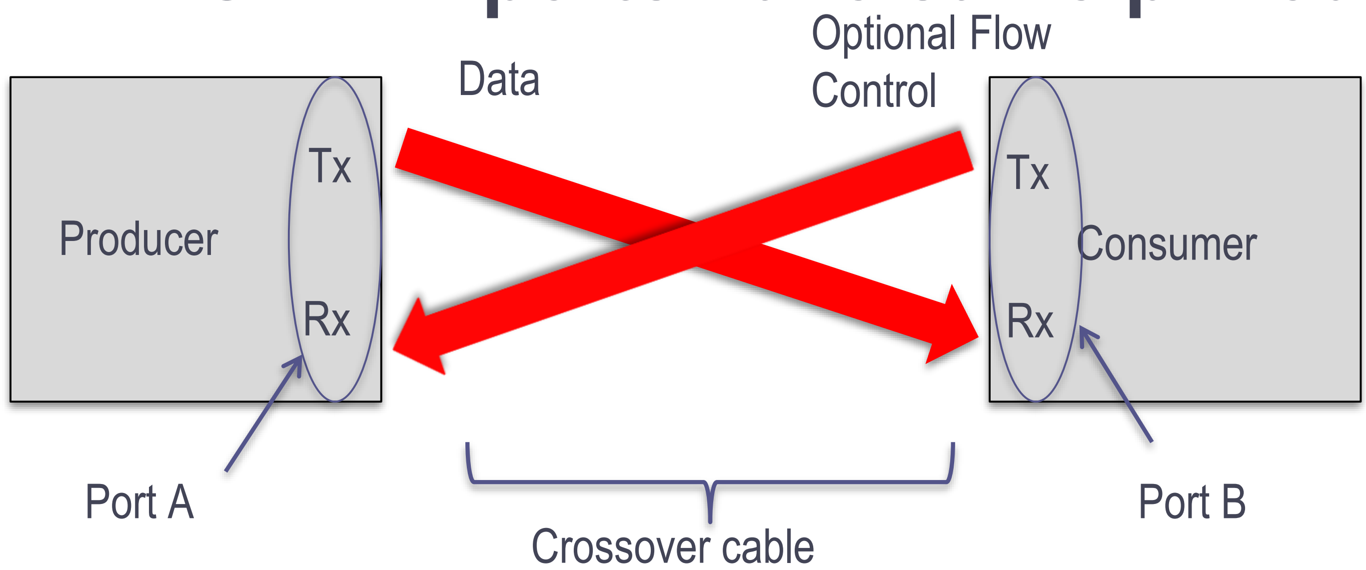


Internal Optical Port Pin Assignments (Shown without the Opposed MPO bulkhead adapter)

	FUNCTION	FIBER COLOR	MPO POSITION
Rx	Rx0	BLUE	1
	Rx1	ORANGE	2
	Rx2	GREEN	3
	Rx3	BROWN	4
	Rx4	SLATE	5
	Rx5	WHITE	6
	Rx6	RED	7
	Rx7	BLACK	8
	Rx8	YELLOW	9
	Rx9	VIOLET	10
	Rx10	ROSE	11
	Rx11	AQUA	12
Tx	Tx0	BLUE (+)	13
	Tx1	ORANGE (+)	14
	Tx2	GREEN (+)	15
	Tx3	BROWN (+)	16
	Tx4	SLATE (+)	17
	Tx5	WHITE (+)	18
	Tx6	RED (+)	19
	Tx7	BLACK (+)	20
	Tx8	YELLOW (+)	21
	Tx9	VIOLET (+)	22
	Tx10	ROSE (+)	23
	Tx11	AQUA (+)	24

- OBSERVATION: An Opposed MPO Adapter changes the Rx fiber side being adjacent to the key (shown) to the Tx signals being adjacent to the keyway as specified in ODI-1.
- OBSERVATION: Many components available use the above pin assignments. An Opposed MPO Adapter will make them compatible with ODI.

OBSERVATION: All ports have same pin-out



- Standard Port has Tx and Rx in same position, regardless if Producer or Consumer
- Standard cable is 12 fibers each direction, in crossover configuration.
- A port is allowed to implement either 12 lanes in either directions, or zero.
- A digitizer may have uni-directional port, while an AWG may have a bi-directional port for flow control

Optics

RULE: ODI-1 devices SHALL comply with the below specifications.
These specifications are essentially 802.3ba specifications, driven at 12.5Gb/s or 14.1 Gb/s.

- Class 1 laser product, meaning no safety issues during normal use
- 850nm multimode transmitters and receivers
- 802.3ba optical levels, driven at up to 14.1Gb/s on each lane
- 12 VCSEL transmitters

OBSERVATION: Optical devices MAY be implemented using the Samtec Firefly system

Optical Ports on Devices

- PERMISSION: A device MAY have one or more optical ports
- Example 1: An instrument may have more than one port to scale the data transfer bandwidth
- Example 2: A processor or storage system may have more than one port to have separate simultaneous data streams
- PERMISSION: It is permissible to place a higher density connector on a product for density reasons, if the vendor also has an adapter to expand to multiple standard connectors.

Line Rates: 12.5Gb/s and 14.1Gb/s

- RULE: All ODI devices SHALL operate at 12.5Gb/s line rate UNLESS the device is unusable at that speed.
- PERMISSION: A ODI device MAY operate at 14.1Gb/s line rate
- OBSERVATION: The above standards essentially mandate a higher speed device to operate at a lower speed if at all possible. This allows an upward compatibility model from 12.5Gb/s to 14.1Gb/s.
- OBSERVATION: Automatically sensing and negotiating line rate is not required. Instead, the system software is expected to command each device to the desired rate. There is no time limit specified for a device to change rates.
- RECOMMENDATION: Certain digitizers and signal generators may require 14.1Gb/s for full performance. Those products SHOULD offer modes that operate at 12.5Gb/s, perhaps by limiting the resolution, number of channels, or sampling rate.
- OBSERVATION: 12.5Gb/s allows the most economical implementation, particularly when FPGA IP costs are considered. 14.1Gb/s allows higher speed implementations where 20GB/s is a critical specification.

Scalable Speed

Today

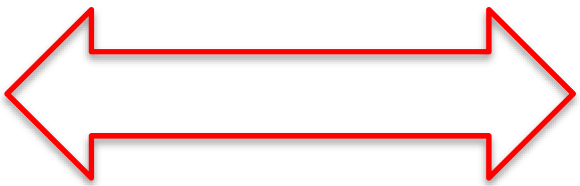
		Link Speed			
		ODI-1		ODI-1.1	ODI-1.2
		12.5G	14.1G	28G	56G
# of Ports	1	17.3GB/s	20GB/s	40GB/s	80GB/s
	2	34.6GB/s	40GB/s	80GB/s	160GB/s
	3	51.9GB/s	60GB/s	120GB/s	240GB/s
	4	69.3GB/s	80GB/s	160GB/s	320GB/s

ODI-2

- Data transfer speeds may be increased by increasing the link speed or by using additional ports (as specified in ODI-2)
- ODI-1 defines the requirements for a single port
- ODI-2 specifies how ports are aggregated to achieve higher speeds
- A higher speed device SHALL operate at lower speeds, unless it becomes unusable
- Higher speeds are planned, to be specified in ODI-1.x specifications

ODI-1 Protocol Layer

Interlaken Interconnect Protocol

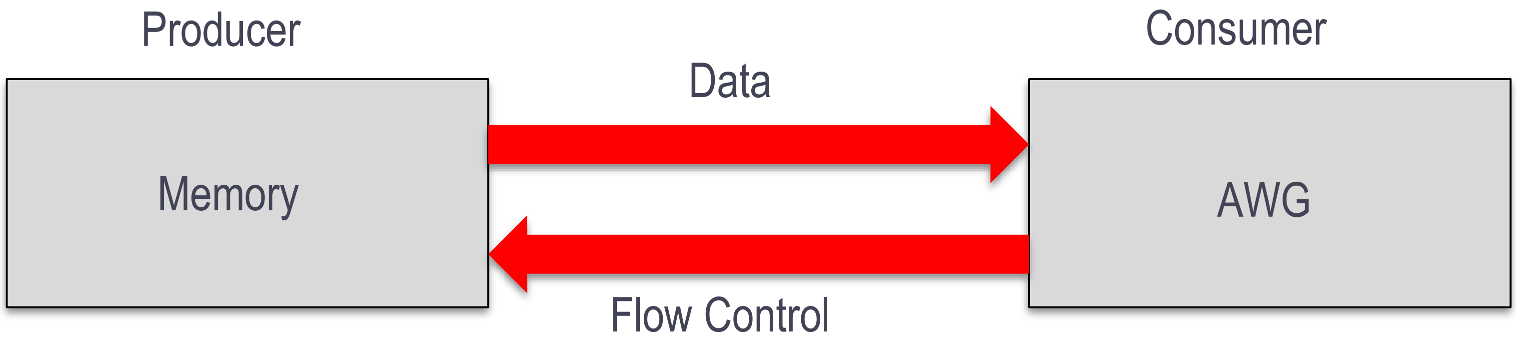


- Packet Framing
- Flow Control
- SerDes Management
- FPGA independent

Protocol Layer

RULE: All implementations of of this specification SHALL comply with all the requirements in the Interlaken Protocol Definition, Revision 1.2 or later.

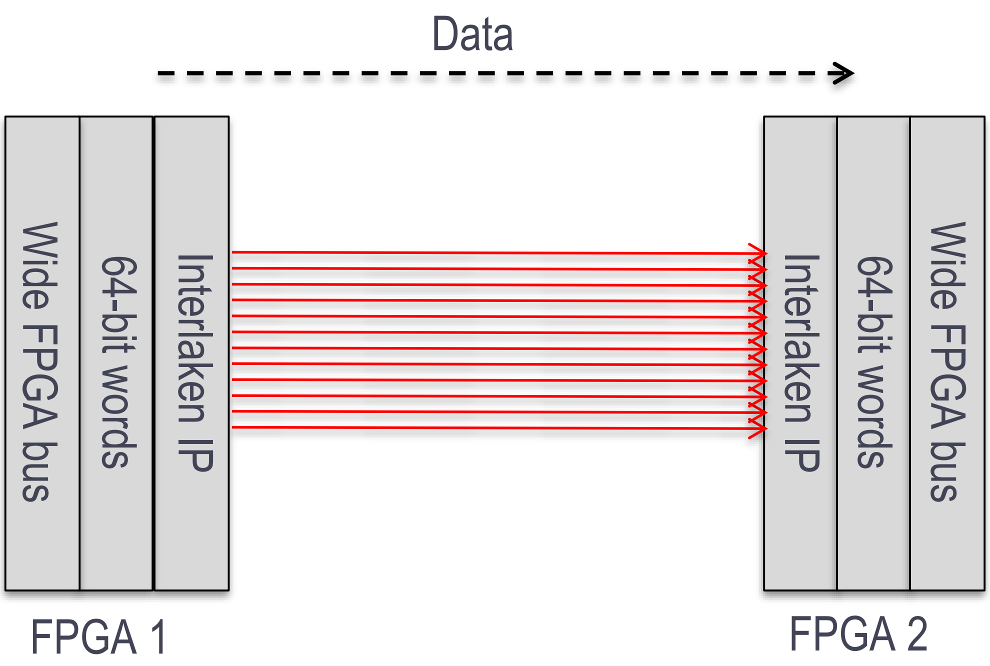
Interlaken chosen as the interconnect protocol



- A proven protocol for high speed chip to chip transfers
- Efficiently packs data over a number of lanes, in this case 12 lanes.
- FPGA vendor-independent
- In-band flow control avoids additional cables between devices
- Out-of-band flow control allows a cost-effective alternative
- Only a single Interlaken channel is typically used.
- Supports long bursts for minimum overhead.
- Supports the transfer of packets, which enables multi-port synchronization

What is Interlaken?

- A chip-to-chip protocol developed by Cortina Systems and Cisco Systems
- Allows wide data patterns typically on FPGAs to be sent over any number of serial links and speed
- Based on 64-bit words, works well with wide FPGA buses
- Includes optional flow control



Interlaken Properties

ODI has chosen chosen certain Interlaken properties to make it most effective at high speed streaming. The table below is from the Interlaken specification, with red text added to specify the ODI implementation of Interlaken

Property	Recommendation	ODI
Backpressure method	In-band	In-band and Out-of-band. Single channel only
Channel count	Not specified, application dependent	One channel minimum.
Packet transfer method	Not specified, application dependent	Packet mode
Packet Mode Stop Boundary	For link level backpressure: Burst end For channel backpressure: Packet end	Burst End
Burst Mode Stop Boundary	Burst	Burst
BurstMax / BurstMin / BurstShort	256 bytes / 64 bytes / 32 bytes	See below, two choices
MetaFrameLength	2,048 words	2,048 words
Multiple use field	Not used	Not used
Rate matching	Yes, 1 Gb/s steps	No. Not used
Status Messaging	Not required	Not required
Retransmission	Optional, default is disabled	No retransmission

BurstMax/Min/Short: 2048 bytes / 64 bytes / 64 bytes
and 256 bytes / 64 bytes / 64 bytes

Channels and data formats

- Signals may have several channels. ODI does not use the Interlaken channel structures for sending data from different signal channels. ODI is designed so that only a single Interlaken channel is needed for streaming multiple synchronous signals. ODI relies on the channel information to be woven into the data stream and packet structure. A typical implementation would be to send the multi-channel data in a round-robin fashion.
- RULE: An ODI device SHALL implement Interlaken Channel 0.
- PERMISSION: An ODI device MAY use more than one Interlaken channel. Performance is unspecified in this situation.
- OBSERVATION: Since synchronous multi-channel data may be encoded into the data stream, multiple Interlaken channels are not necessary. However, there may be a case where asynchronous data, such as temperature, may be sent on a second Interlaken channel.

Interlaken Protocols: BurstMax

- Interlaken sends data through a series of data bursts. In most cases, the length of the data burst is a parameter labeled BurstMax

- Longer BurstMax is more efficient. 256 BurstMax IP is often free.

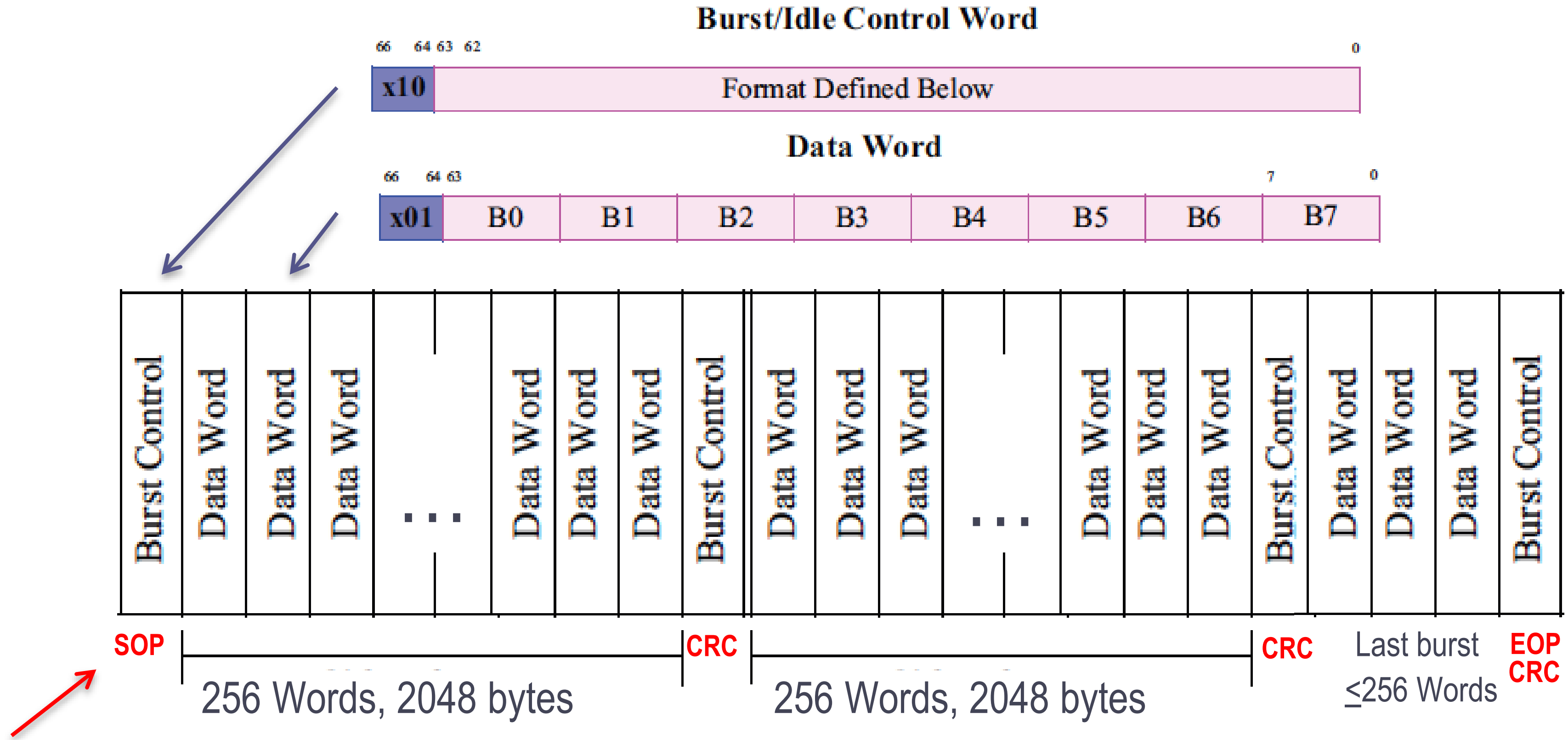
- ODI specifies two BurstMax options.
  - 256 bytes at 12.5Gb/s line rate for economy applications
  - 2048 bytes at 14.1Gb/s for performance applications

- RULE: All 12.5Gb/s producers SHALL transfer data using 256 byte BurstMax
- RULE: All 14.1Gb/s producers SHALL transfer data using 2048 byte BurstMax

- RULE: Higher speed devices (e.g. 14.1Gb/s) SHALL operate at lower speeds, including the appropriate BurstMax UNLESS the device is unusable at the lower speed

Interlaken burst framing at 14.1Gb/s set at 256 words = 2048 bytes

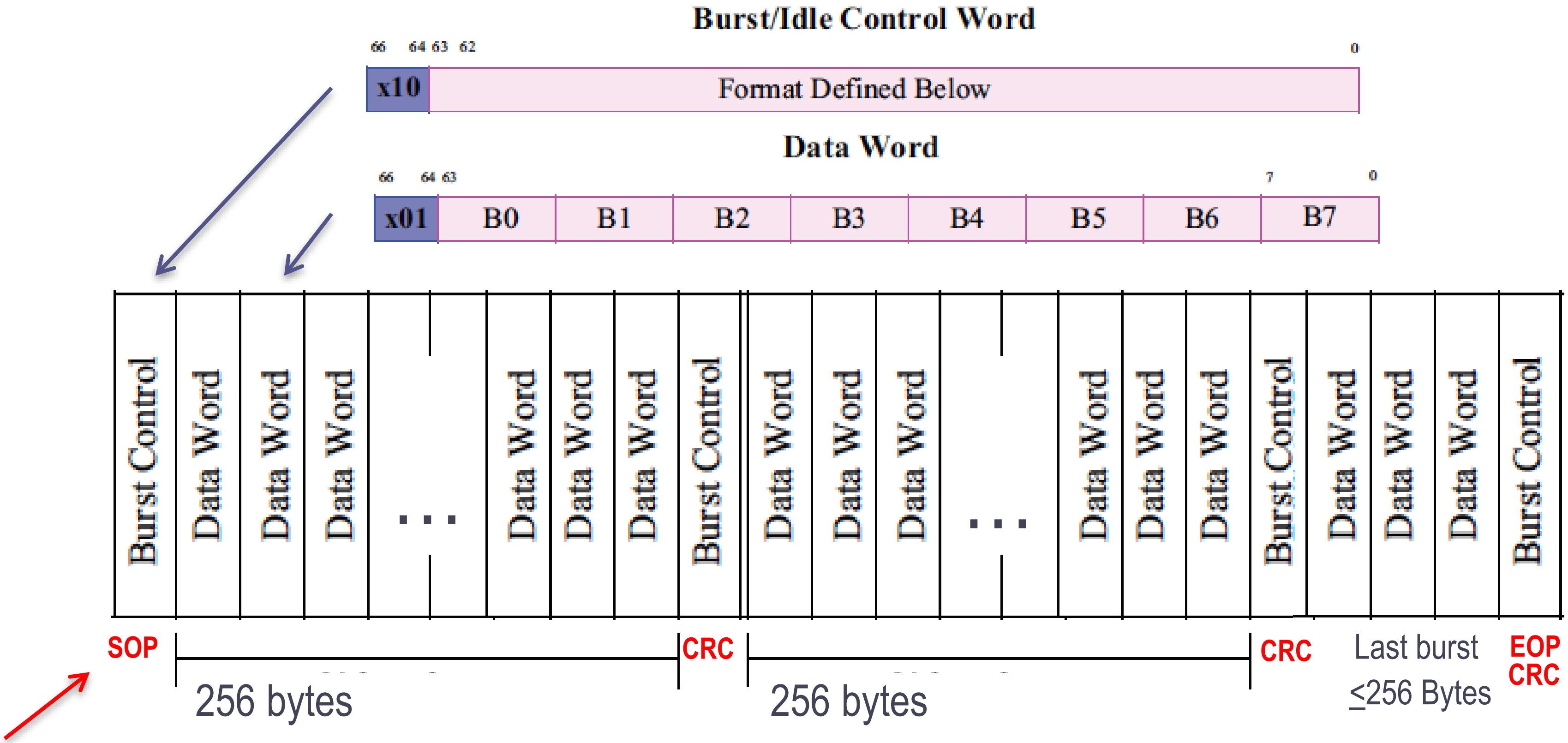
Burst framing sends the data in 2K byte chunks



Start of Packet and End of Packet encapsulate one packet.

Interlaken burst framing at 12.5Gb/s set at 256 bytes

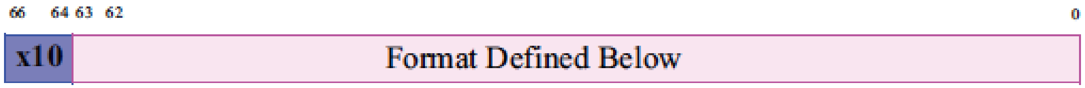
Burst framing sends the data in 256 byte chunks

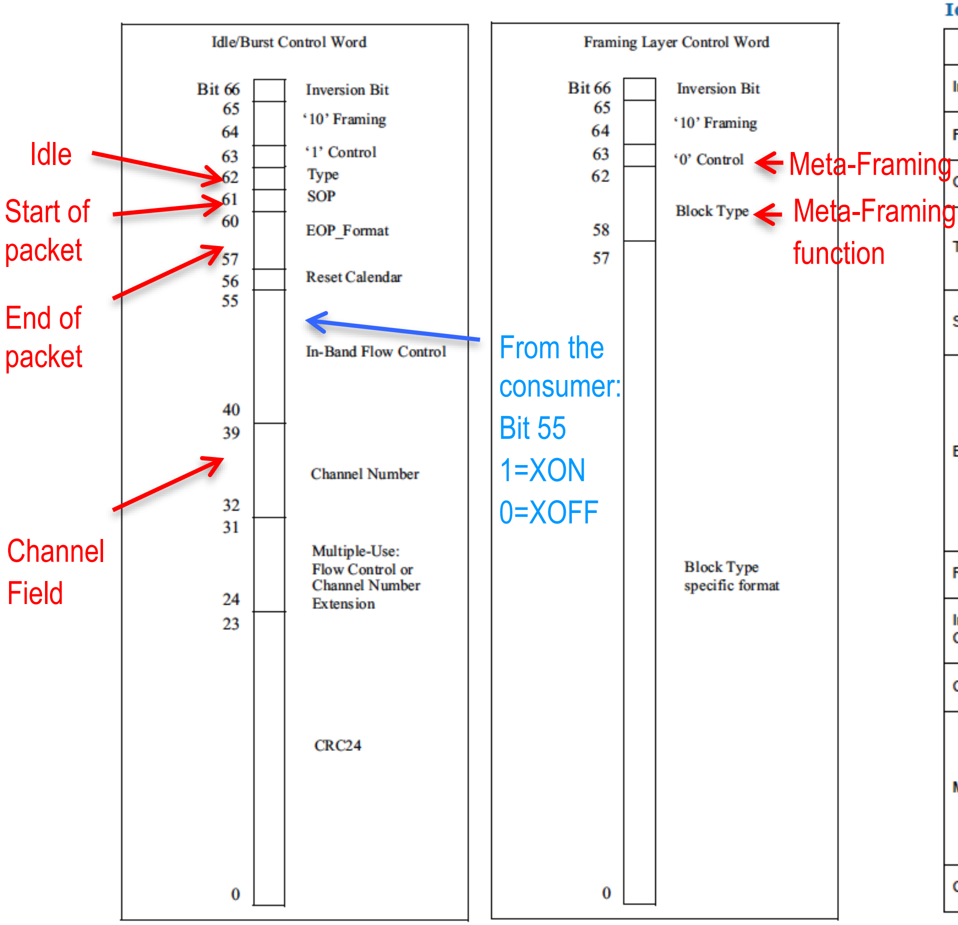


Start of Packet and End of Packet encapsulate one packet.

Interlaken Control Words

Burst/Idle Control Word





Burst Control Word

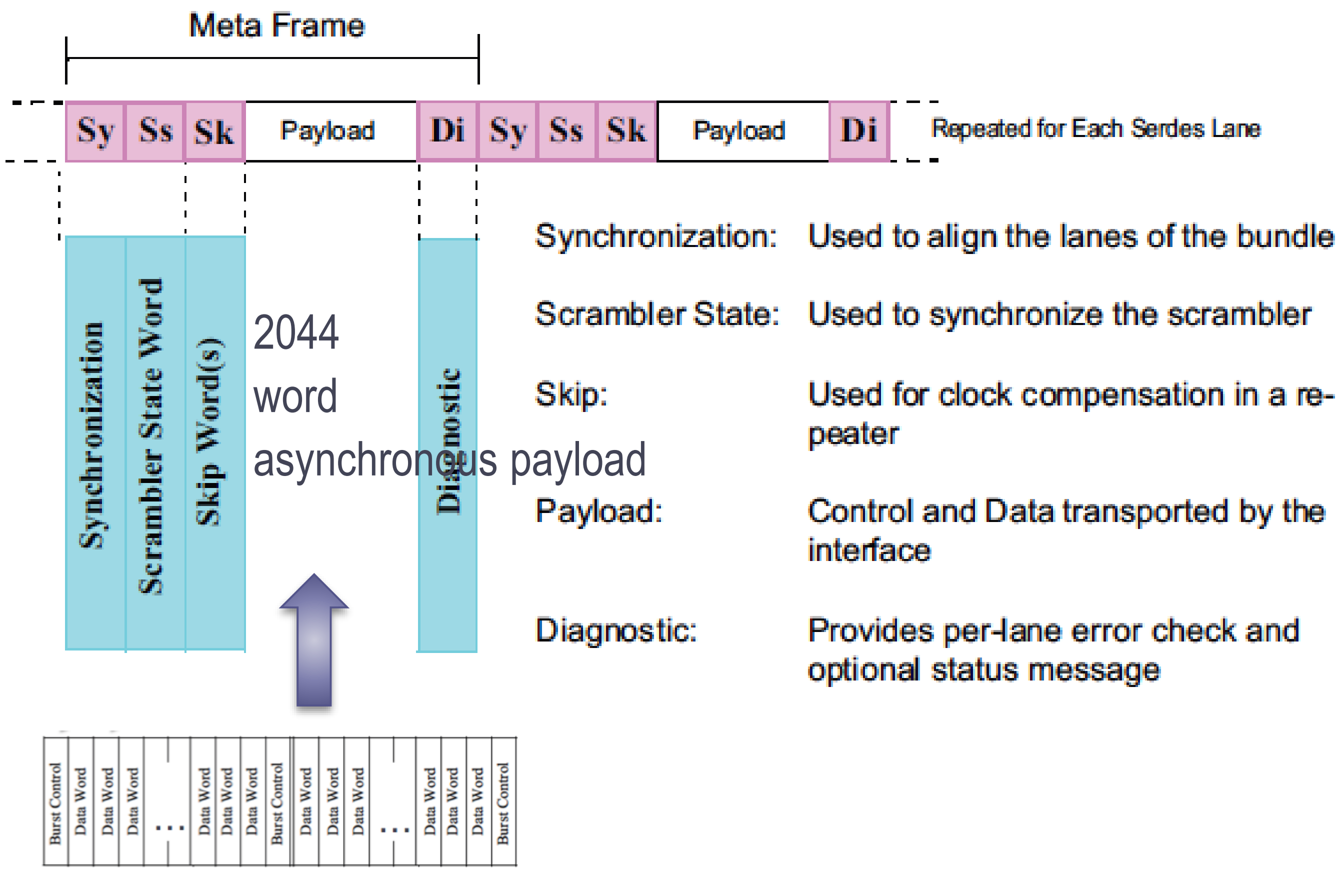
Meta framing Control Word

Idle/Burst Control Word Format

Field	Bit Position	Function
Inversion	66	Used to indicate whether bits [63:0] have been inverted to limit the running disparity; 1 = inverted, 0 = not inverted
Framing	65:64	64B/67B mechanism to distinguish control and data words; a '01' indicates data, and a '10' indicates control
Control	63	If set to '1', this is an Idle or Burst Control Word; if '0', this is a Framing Layer Control Word (see Section 5.4, *Framing Layer*, on page 26)
Type	62	If set to a '1', the channel number and SOP fields are valid and a data burst follows this control word (a 'Burst Control Word'); if set to a '0', the channel number field and SOP fields are invalid and no data follows this control word (an 'Idle Control Word')
SOP	61	Start of Packet. If set to a '1', the data burst following this control word represents the start of a data packet; if set to a '0', a data burst that follows this control word is either the middle or end of a packet
EOP_Format	60:57	This field refers to the data burst preceding this control word. It is encoded as follows: '1xxx' - End-of-Packet, with bits[59:57] defining the number of valid bytes in the last 8-byte word in the burst. Bits[59:57] are encoded such that '000' means 8 bytes valid, '001' means 1 byte valid, etc., with '111' meaning 7 bytes valid; the valid bytes start with bit position [63:56] '0000' - no End-of-Packet, no ERR '0001' - Error and End-of-Packet All other combinations are left undefined.
Reset Calendar	56	If set to a '1', indicates that the in-band flow control status represents the beginning of the channel calendar
In-Band Flow Control	55:40	The 1-bit flow control status for the current 16 calendar entries; if set to a '1' the channel or channels represented by the calendar entry is XON, if set to a '0' the channel represented by the calendar entry is XOFF
Channel Number	39:32	The channel associated with the data burst following this control word; set to all zeroes for Idle Control Words
Multiple-Use	31:24	This field may serve multiple purposes, depending on the application. If additional channels beyond 256 are required, these 8 bits may be used as a Channel Number Extension, representing the 8 least significant bits of the Channel Number. If additional in-band flow control bits are desired, these bits may be used to represent the flow control status for the 8 calendar entries following the 16 calendar entries represented in bits[55:40]. These bits may also be reserved for application-specific purposes beyond the scope of this specification.
CRC24	23:0	A CRC error check that covers the previous data burst (if any) and this control word

Interlaken framing choices
Meta Framing, set at 2048 words

Meta framing maintains the health of the serial links



Speed is dependent on Interlaken choices

- 14.1Gb/s leads to raw speed of 21.15GB/s
- Standard 64/67 Interlaken decoding reduces speed by ~4.5%
- Length of bursts (called BurstMax in Interlaken parlance) reduces speed due to finite overhead for each burst of 8 bytes (one word)
  - Therefore a common BurstMax of 256 bytes reduces speed ~3%
  - A longer BurstMax of 256 words (2048 bytes) reduces speed ~0.6%
  - ODI specifies both of these.
- Assume no loss due to alignment efficiency
- Metaframes require 4 words every 2048 words, reduces speed ~0.2%

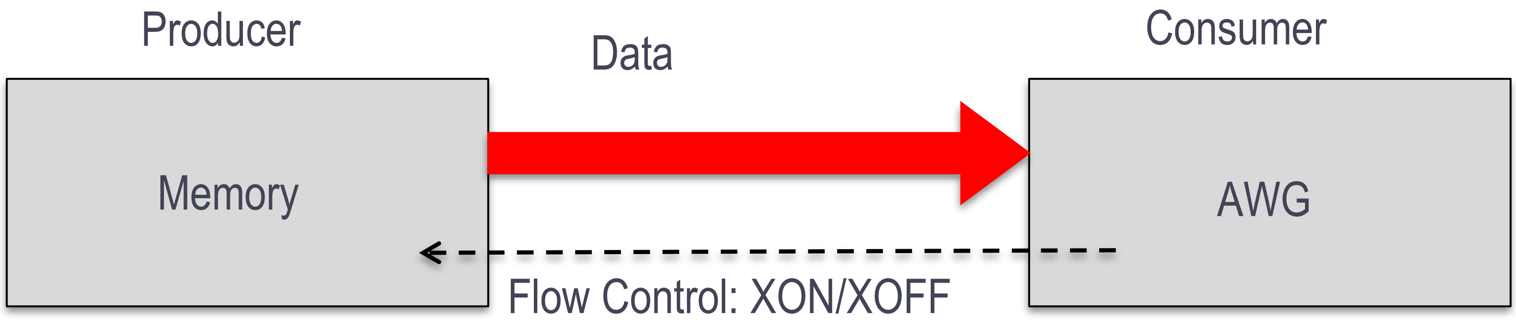
Speed Calculation – 14.1Gb/s, long BurstMax

- 14.1 Gb/s x 12 lanes / 8 bits/byte => 21.15GB/sec raw channel speed
- 64/67 coding = 95.52% efficiency => 20.20GB/sec coded speed
- 256 word (2K byte) burst framing = 256 words/257 words
  = 99.61% efficiency
  => 20.12GB/sec framed speed
- Alignment efficiency = 100%. => 20.12GB/sec aligned frame speed
- 2048 Metaframing = 2044 words/2048 words = 99.8% efficiency
  => 20.09GB/sec total speed

Speed Calculation – 12.5Gb/s, short BurstMax

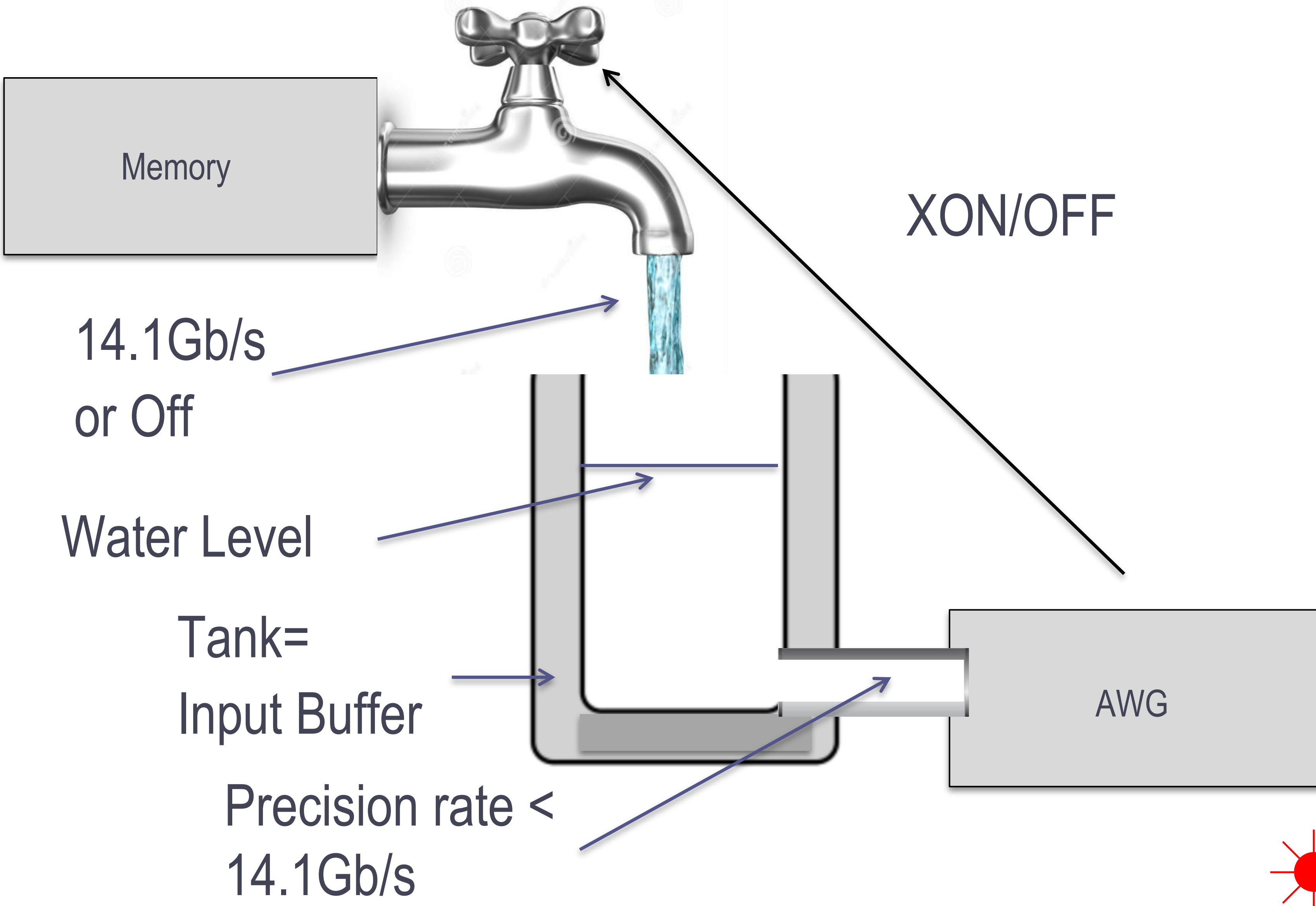
- 12.5 Gb/s x 12 lanes / 8 bits/byte => 18.75GB/sec raw channel speed
- 64/67 coding = 95.52% efficiency => 17.91GB/sec coded speed
- 256 byte burst framing = 256 bytes/264 bytes
  = 96.97% efficiency
  => 17.37GB/sec framed speed
- Alignment efficiency = 100%. => 19.59GB/sec aligned frame speed
- 2048 Metaframing = 2044 words/2048 words = 99.8% efficiency
  => 17.33GB/sec total speed

Flow Control



- **Optional** flow control allows a consumer to to modulate the rate of the data being sent to it by sending a signal **XON/XOFF** (Transmit ON, Transmit OFF) to the producer.
- The flow control signal XON/XOFF may either be sent "**In Band**" (IB) or "**Out of Band**" (OOB). That is, it may be sent via a **reverse Interlaken link**, or as a **separate electrical or optical signal**.
- **Consumers such as AWGs** and other signal generators are likely to implement flow control to keep the incoming data patterns matched with their sampling speed
- **Producers such as digitizers** are more likely to **not** implement flow control, since they must generate data at their sampling speed.
- **Memory, other storage devices**, and processors are likely to implement **both**, flow control and no flow control, to interface with all instrument types.

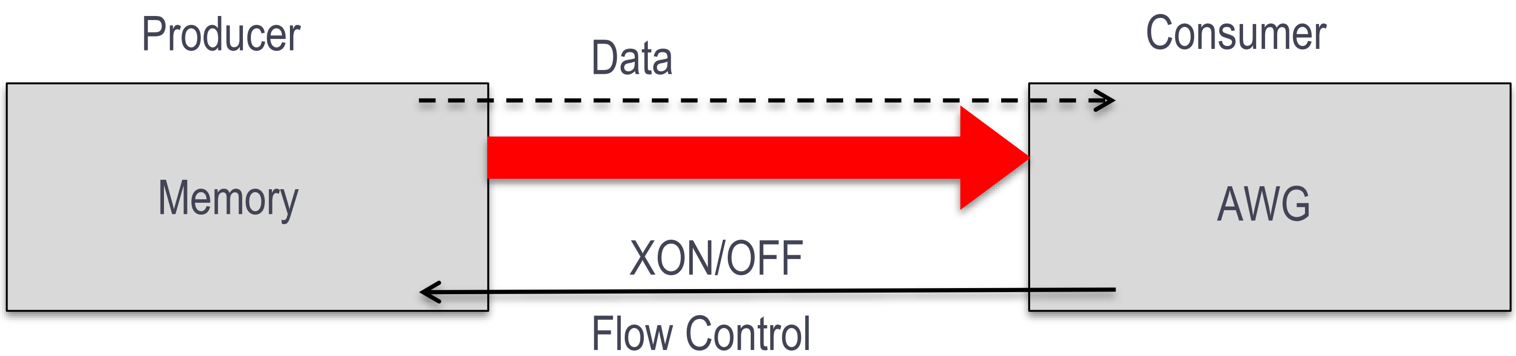
Flow Control – Analogy to a water tank



Flow Control – In Band

- In band flow control is implemented over the optical cable by the consuming device sending Interlaken XON and XOFF commands (shown above) over the optical reverse path.
- XON causes the producer to send data at its full rate.
- When a consumer detects that its input buffers are getting close to full, it then indicates XOFF, forcing the producer to stop transmitting after it has completed the current Interlaken burst.
- When the consumer detects that the buffer is sufficiently depleted, but before it is empty, it indicates the XON command to the producer to resume transmitting.
- This protocol allows the consumer to pace the data being sent to it.
- RULE: An ODI-1 consumer SHALL use Interlaken Control Word Bit 55 to signal XON/XOFF

Flow Control – Out of Band



- Out of band flow control operates identically to In Band, except that the XON/XOFF signal is indicated over an electrical or optical wire.
- Electrical flow control allows unidirectional optical ports to implement flow control without the cost of a reverse optical link.
- RECOMMENDATION: A device that implements flow control SHOULD have an external electrical connector that implements XON/XOFF for each optical port.
- RECOMMENDATION: AXIe and PXI modular devices SHOULD implement electrical flow control using the backplane trigger lines, one line per port controlled.
- RULE: If Out of Band flow control is implemented on a PXI or AXIe device, each flow control signal SHALL be programmable to use any of the backplane trigger lines.
- When using an electrical connection, 1=XON, and 0=XOFF

Packets

ODI has adopted a packet architecture where data is streamed as consecutive packets. This allows robust resynchronization in case of a data link lapse, and allows port aggregation by higher ODI standards. ODI-1 requires data to be sent as packets, while ODI-2 and ODI-2.1 specifies the structure of the packets.

- Packets are bracketed by Interlaken SOP and EOP signals
  (Start of Packet and End of Packet signals)
- Consecutive packets are sent to stream data
- Packets contain single channel or multi-channel sample data
- Packets boundaries allow for error recovery of multi-channel data in the event of a temporary link outage
- Stored data is stored as packets

- Packets allow port aggregation and synchronization (ODI-2)
- Packets are independent of the underlying transmission method
- Packets may be made compliant to VITA 49.2 standard (ODI-2 and ODI-2.1)

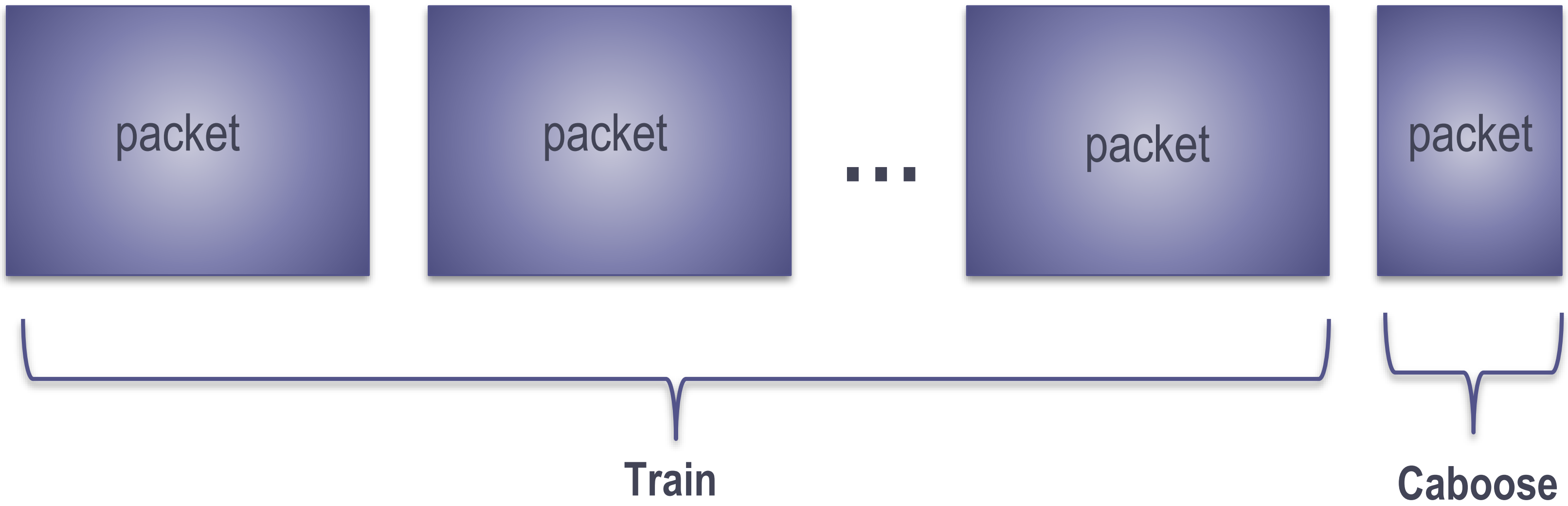
Packet rules

- RULE: An ODI producer SHALL send data as consecutive Interlaken packets
- RULE: An ODI producer SHALL start each packet with the Interlaken SOP (Start of Packet) signal.
- RULE: An ODI producer SHALL end each packet with the Interlaken EOP (End of Packet) signal.
- PERMISSION: An ODI producer MAY send EOP and SOP in the same control word between two packets
- OBSERVATION: Sending EOP with SOP increases the efficiency of data streaming by inserting just one packet boundary control word between data packets instead of two.
- OBSERVATION: Longer packets lead to higher efficiency as the number of SOP/EOP control words decrease.
- RULE: All Interlaken packets SHALL be an integer number of 32 bytes in length
- OBSERVATION: By making packet lengths divisible by 32, FPGA design may be simplified.
- RULE: A packet SHALL NOT exceed 256KB in length
- OBSERVATION: The longest VRT packet is slightly less than 256K
- RECOMMENDATION: Developers SHOULD calculate the minimum packet length needed to meet the overall speed requirement, and exceed that number.

OSE and packet length

- ODI has specified Interlaken BurstShort to be 64 bytes. This means that no burst may be shorter than 64 bytes. For certain combinations of BurstMax and packet length, this can lead to inefficiency as idle words are sent during the last burst to extend it to 64 bytes. This may occur if the the packet length is an odd multiple of 32 bytes.
- Interlaken has specified an Optional Scheduling Enhancement (OSE) to handle this situation. OSE works by sending a shorter burst length for the second to last burst so that the final burst will be at least 64 bytes. This eliminates ever sending Idle words in a packet to comply with the BurstShort spec. This is performed in the FPGA IP by specifying an additional parameter BurstMin, and setting it at 64 bytes.
- RECOMMENDATION: To maximize efficiency, a producer SHOULD use OSE if there are cases where packet length is an odd multiple of 32 bytes.
- OBSERVATION: OSE is entirely implemented by the producer. A consumer will automatically adapt to a producer using OSE.
- OBSERVATION: The key aspect for efficiency will be to have sufficient packet length that the overhead of the packet plus an extra burst control word is small.
- A 32K length packet (words) creates 0.05% inefficiency worse case, which is 1/10 of the remaining margin (0.5%) to achieve 20GB/s per port. Therefore, packet sizes between 32K and 64K (max) would all achieve the efficiency needed when coupled to OSE.

Streaming - 1

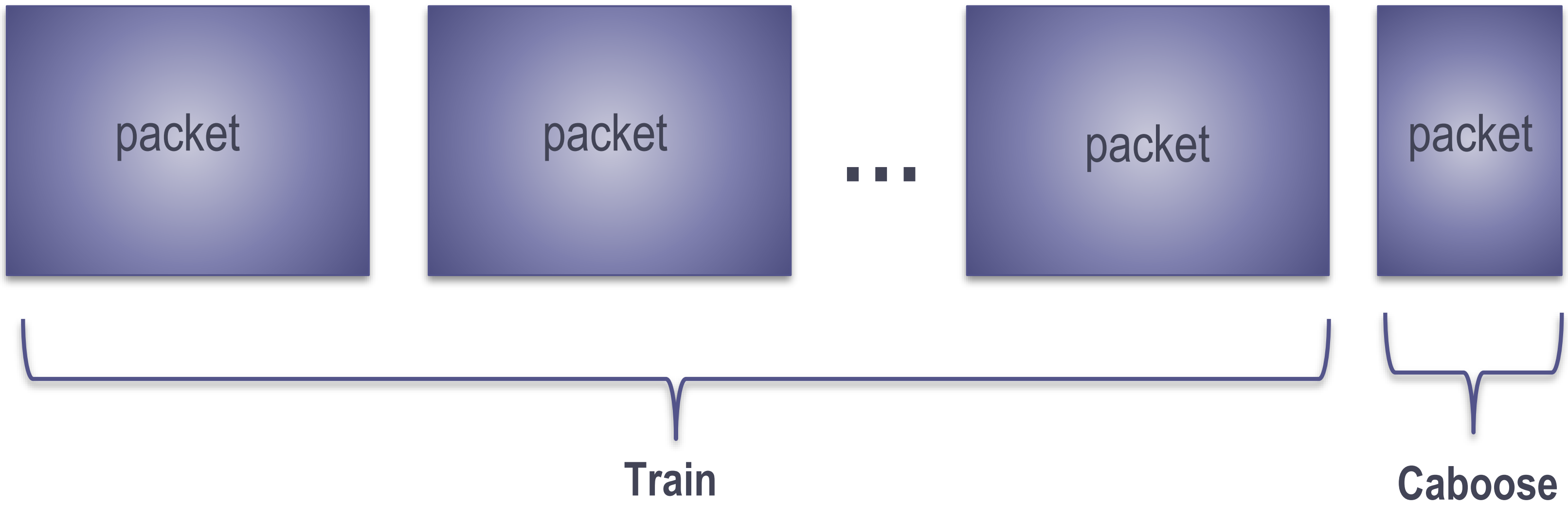


Streaming is performed by transmitting a series of packets consecutively in a “train”. These packets are designed for efficiency, and typically are of the same length and number of samples.

When streaming ends, the final packet is called the caboose. It may be the same size as the previous packets, or it could be smaller.

OBSERVATION: A ODI-1 recording device can record a stream without knowledge of the format of the data packets, and play them back to another ODI device.

Streaming - 2

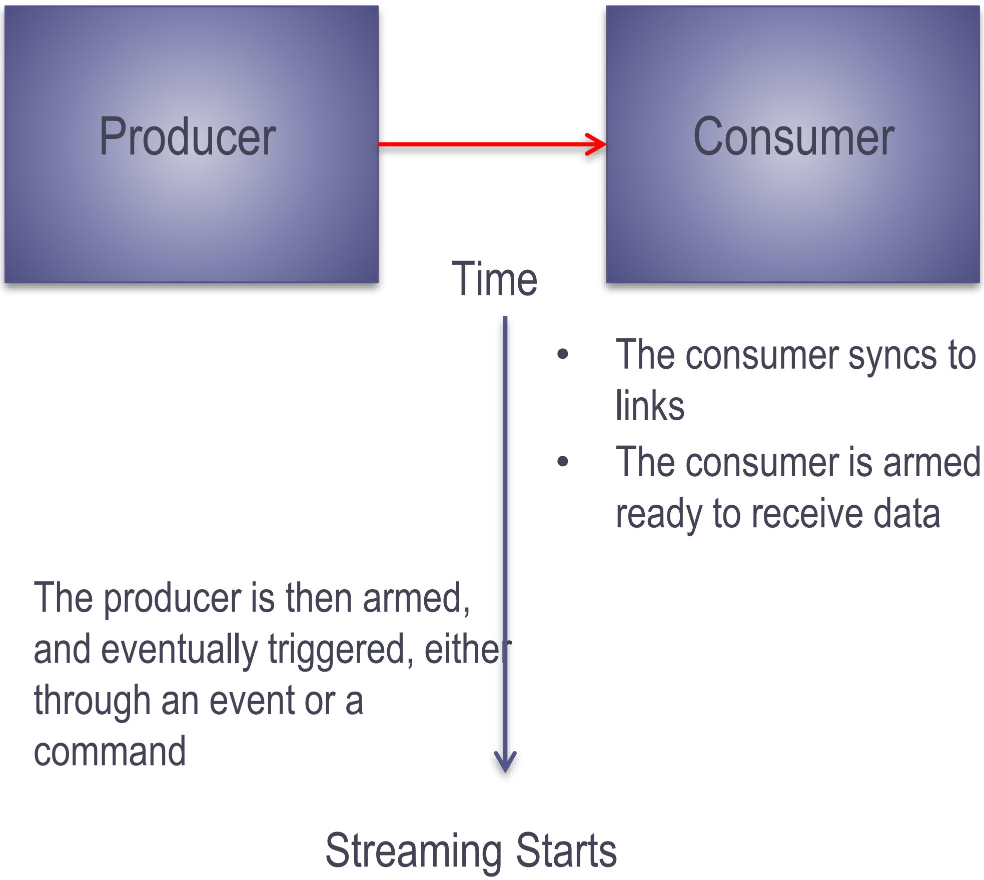


The producer has considerable flexibility in the length of each packet. It is up to the producer to choose packet lengths that will allow the full streaming speed to be supported over an ODI link. Typically, this is done by choosing packets sufficiently long so that the non-data overhead (e.g. VRT Prologue and Interlaken control words) is minimized.

Often, the producer can choose to make the Caboose the same length as other packets. A digitizer, for example, may send a Caboose packet of the same exact length as the others once it has received a “Stop Streaming” command.

The producer may also use FPGA IP that signals Interlaken SOP and EOP simultaneously between packets to reduce Interlaken overhead to a single control word.

Streaming – Time Diagram (1)



- The consumer syncs to the ODI links
- The consumer is armed first, ready to receive data

- The producer is then armed, and eventually triggered, either through an event or a command

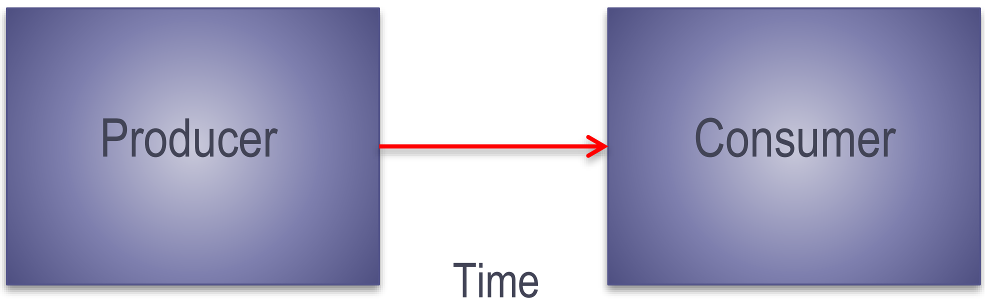
The ODI specifications assume that certain sequences of commands are occurring at the system level.

For example, the consumer is armed first.

Once the consumer is armed, the producer is then armed.

Finally, the producer is triggered, and streaming begins.

Streaming – Time Diagram (2)



Time

- Streaming in progress
- The producer receives a “Stop” event- either via a command or signal.
- The producer sends the Caboose, and stops sending further data.
- The producer goes into the “Unarmed” state.

- Streaming in progress

- A “Stop” command is sent to the consumer, which returns to an unarmed state.

Streaming Complete

To end streaming, the reverse occurs.

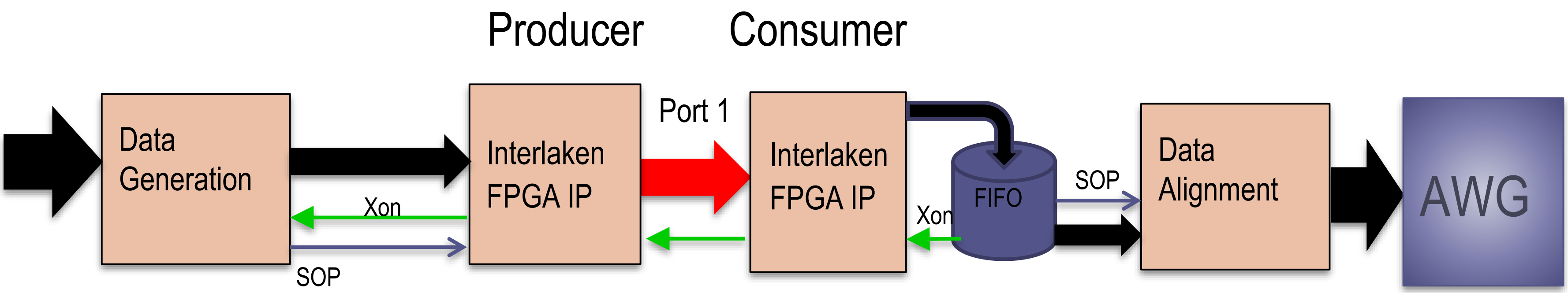
A “stop event” is sent to the producer. This is typically a command, but could also be an electrical trigger signal or a value in the data.

The producer sends the Caboose, and returns to the “Unarmed” state.

Once confirmed, the system sends a stop command to the consumer.

Producer and Consumer end in the unarmed state.

Flow Control Operation – Single Port

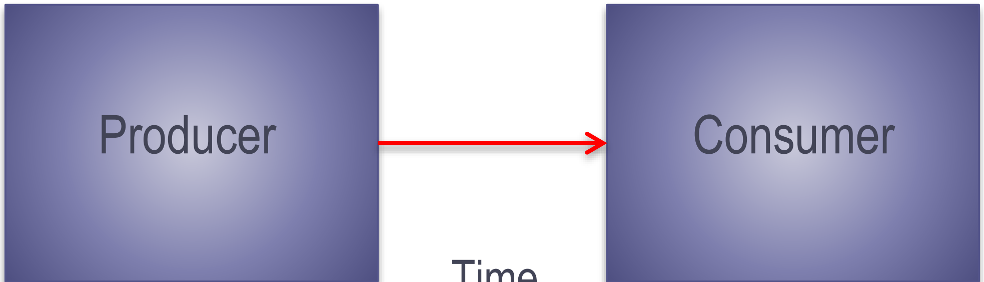


Flow control is performed by the Consumer indicating to the producer whether data is to be sent, or not. This is done by indicating XON (transmit) and XOFF (halt transmit) either through the reverse optical connection (in-band) or an external signal (out-of-band).

In the above example, the producer is delivering data to the consumer, an AWG. The producer sends SOP to align the data freshly for every new packet. Data follows until the end of packet, where SOP is sent again for the next packet.

The consumer, by monitoring the amount of data in the FIFO, indicates XON/XOFF to the producer. The Producer halts the sending of data when an XOFF is indicated, and resumes the sending of data when XON is indicated.

Streaming – with Flow Control (1)



Time

- The consumer syncs to the ODI links
- The consumer sets XOFF

- The producer is enabled to send data

- The consumer sets XON and loads data into its buffer until nearly full. It then sets XOFF.
- The consumer is armed. When a trigger event occurs, the consumer begins operating on the data (e.g. playing a waveform).

Streaming Starts

For flow control, the sequence is similar, but the consumer's control of XON and XOFF determines when data is transferred.

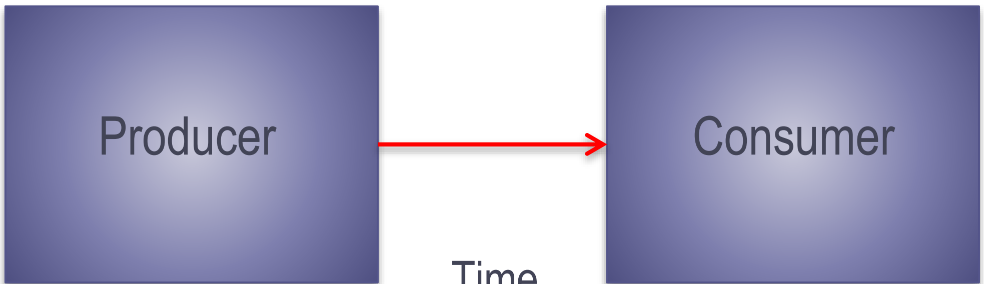
The consumer syncs to the ODI links, and indicates XOFF.

The producer is enabled to send data whenever it sees XON.

The consumer loads the data into its buffer, then indicates XOFF.

The consumer will operate on the data when it is triggered.

Streaming – with Flow Control (2)



Time

- Streaming starts with XOFF.
- Once the producer sees XON, it sends more data
- The producer stops sending data when it sees the XOFF

- The consumer begins executing the data while XOFF. When the buffer becomes near empty, the consumer will set XON.
- The consumer will set XOFF when the buffer becomes near full
- A “Stop” command is sent to the consumer, which returns to an unarmed state.

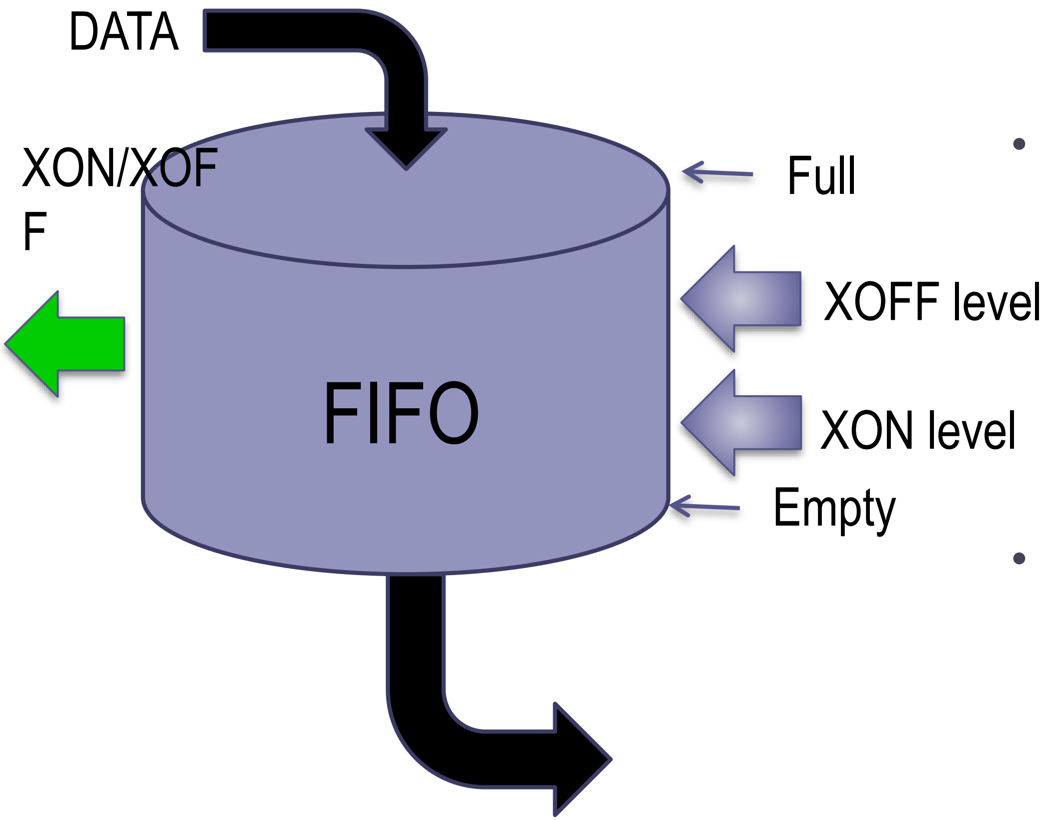
Streaming Complete

During the streaming process, the consumer is managing its input buffer as shown to the left.

The consumer is continuously processing the data in the buffer.

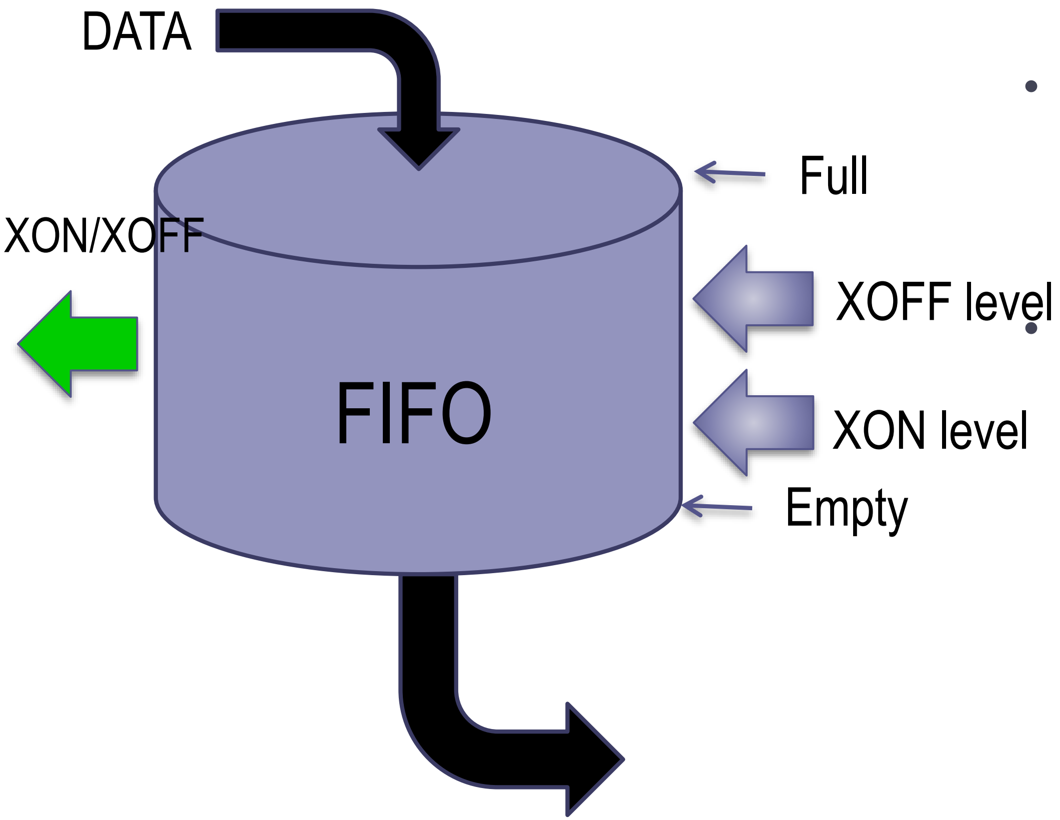
The process can loop indefinitely until there is a STOP command to the consumer. At a convenient stopping point, the consumer will indicate one more “XOFF”, and go into an unarmed state

FIFO Timing (1)



- The figure to the left models the operation of the FIFO from the previous diagram.
- When the FIFO nears empty, it triggers XON to begin filling the FIFO. The FIFO fills at RP-RC, where RP is the rate of the producer (typically the ODI rate) and RC is the operation rate of the consumer.
- Since RP > RC, the FIFO fills until it reaches the XOFF level. When reached, XOFF is indicated, and Data transmission ceases.
- The FIFO will empty at the rate RC until it reaches the XON level.
- Note that there can be significant delay between when XON/XOFF is indicated, and the FIFO sees the change in data transmission.

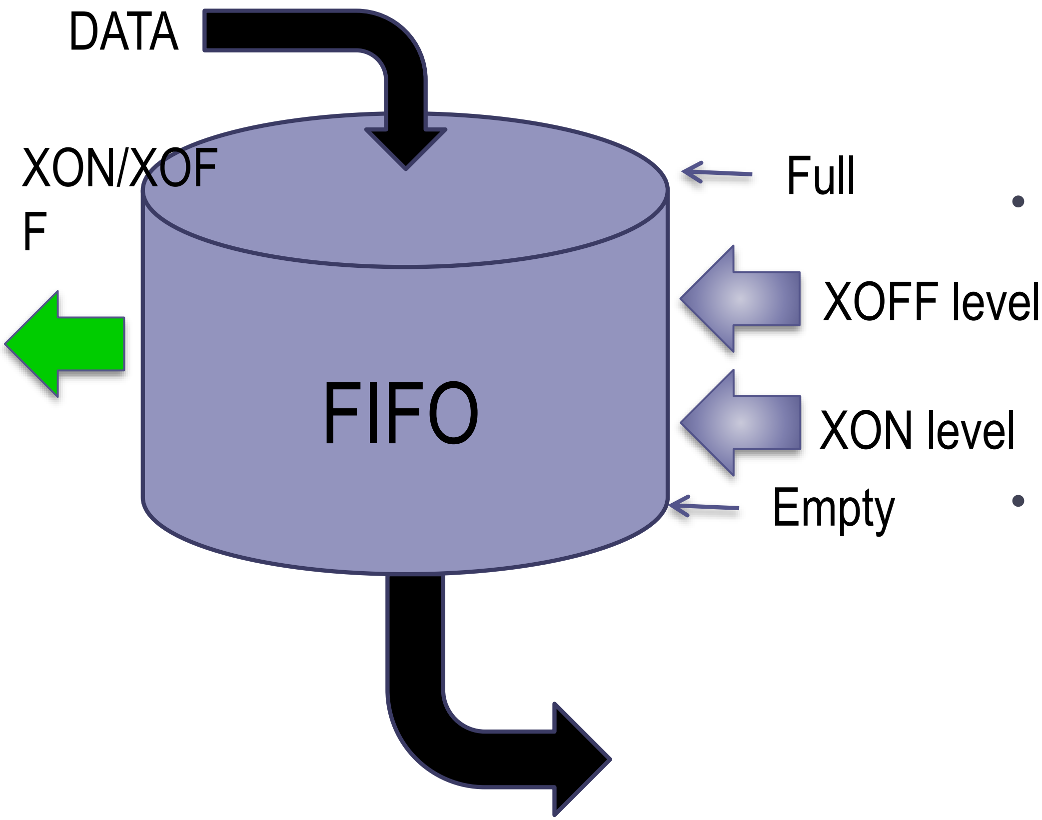
FIFO Timing (2)



- The fill rate is RP-RC. Since RC may be low, the maximum fill rate is RC.
- The emptying rate is RC. Since RC must be lower than RP, the maximum emptying rate is RP.
- A producer cannot change between XON and XOFF until the next Burst. Therefore, the theoretical minimum latency is one BurstMax. ODI specifies a much longer latency to accommodate pipeline processing. For ODI, the Producer MUST transition between XON/XOFF within 450 ns.

To ensure margin:
The producer SHALL respond to an XON/XOFF indicator within 450 ns.
The consumer XON level SHALL be set to accommodate up to 900 ns of flow control reaction time.
The consumer XOFF level SHALL be set to accommodate up to 900 ns of flow control reaction time.

FIFO Timing (3)



- PERMISSION: The consumer MAY choose a single level for XON and XOFF if the level meets the requirements for both.
- OBSERVATION: The minimum FIFO size is 2 x 900 ns, multiplied by the data rate. This corresponds to 36,000 bytes at full rate.
- RECOMMENDATION: The Producer should choose a data packet size larger than 36 Kbytes, so that a maximum of one data packet SOP is in the FIFO at any one time. This is helpful in port aggregation.

- NOTE: The producer and consumer specifications for flow control assume certain latencies in Interlaken IP. Once these latencies are more thoroughly characterized, the required response times may change.

State Diagrams – single port

ODI-1 defines a method for streaming data, regardless of the packet format. For ODI-1, a generic packet is assumed to be packet data encapsulated with an optional prologue before the data and an optional trailer after the packet. Another way to think about this is that either the prologue or the trailer may be zero words, or any number of words.

The following state diagrams will refer to prologue and trailers, whether they exist or not. If they don't exist for the given packet, they will refer to the beginning of data and end of data respectively.

SOP	
Prologue...	Data
Data	Data
Data	Data
Data	Data
Data	Data
Data	Data
Data	Data
Data	Data
Data	...Trailer
EOP	

<- Packet begins with optional prologue of undefined length.

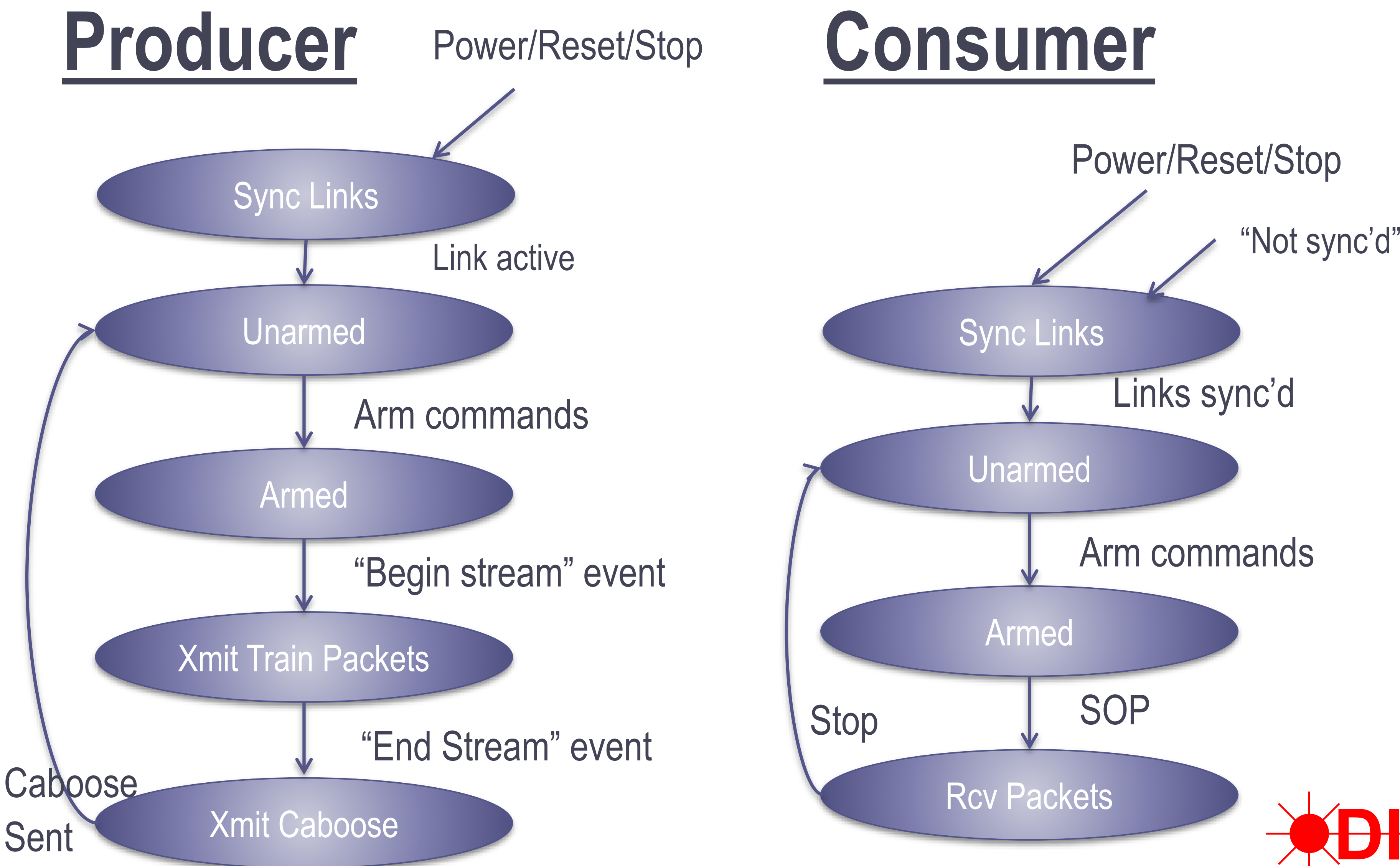
Generic Packet

<- Packet ends with optional trailer of undefined length.

State Diagram Overall, Terms

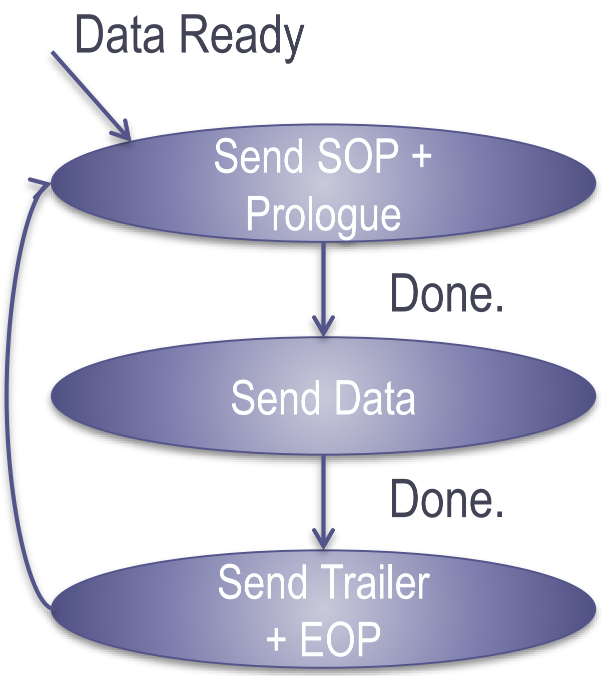
- Power/Reset
  - Power on event or Reset command
- Stop
  - A Stop command unarms the Consumer, typically at end of streaming
- Arm Commands
  - Arm commands set up the Producer and Consumer pre-streaming
  - The consumer is ready to accept data once in the Armed state
  - The producer, in an Armed state, will send data once a Begin Stream event occurs
- Begin Stream
  - …is an event that “triggers” the Producer to begin sending data
  - Begin Stream may be a command, a trigger event, or other event.
- Xmit Train Packets
  - The Producer sends (typically) large “train” packets, one after the other, to the Consumer. It will do so until an End Stream event occurs.
- Xmit Caboose
  - The Producer sends the final packet. This packet may by shorter than the train packets
- End Stream
  - …is an event that signals end of streaming. It can be a a command from the controller to the producer, or it can be generated by a storage device recognizing only one packet left to be transmitted
- SOP
  - =Interlaken Start of Packet.
- Rcv Packets
  - The Consumer goes into Receive Packet mode after receiving the first SOP
  - The Consumer exits Rcv Packets mode only via a Stop command, usually sent after the acquisition is done.

Streaming state diagram: Overall



State diagram: Xmit Train Packets

Producer



The Xmit Train Packets state is shown to the left.

The actions show the interaction with the FPGA IP. Though “Send SOP + Prologue” is shown as one command, the FPGA IP will sequence the SOP first, to be followed by the Prologue.

Similarly, though “Send Trailer + EOP” is shown as one command, the EOP is sent after the Trailer ends.

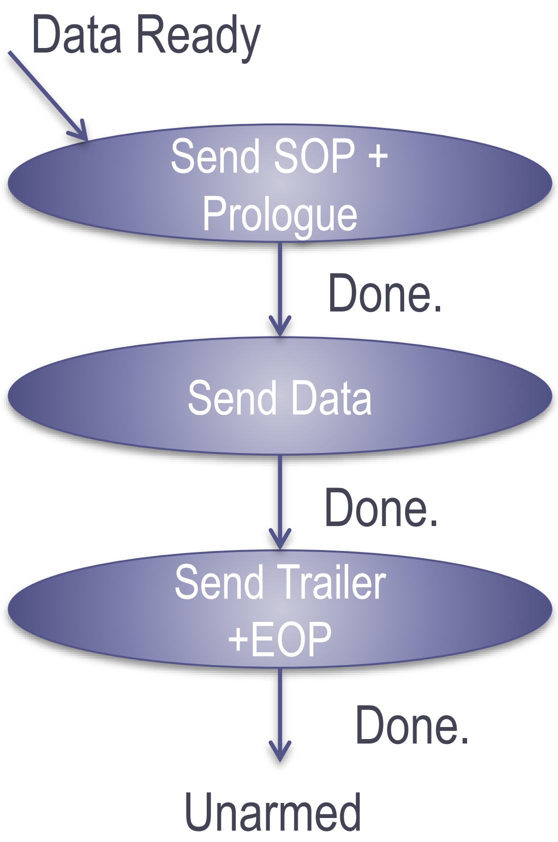
Note: Though EOP and SOP are shown as independent actions, a likely outcome will be that EOP and SOP are both set in the single Interlaken control word between packets, minimizing overhead.

Note: “Send Data” includes sending null data, if necessary, before the trailer to ensure entire packet is a multiple of 32 bytes.

With Flow Control:

- The diagram to the left shows operation with XON=1
- Of XON=0, data transmission stops within the length of 8 BurstMax.

State diagram: Xmit Caboose Packet Producer



The Xmit Caboose Packets state is shown to the left.

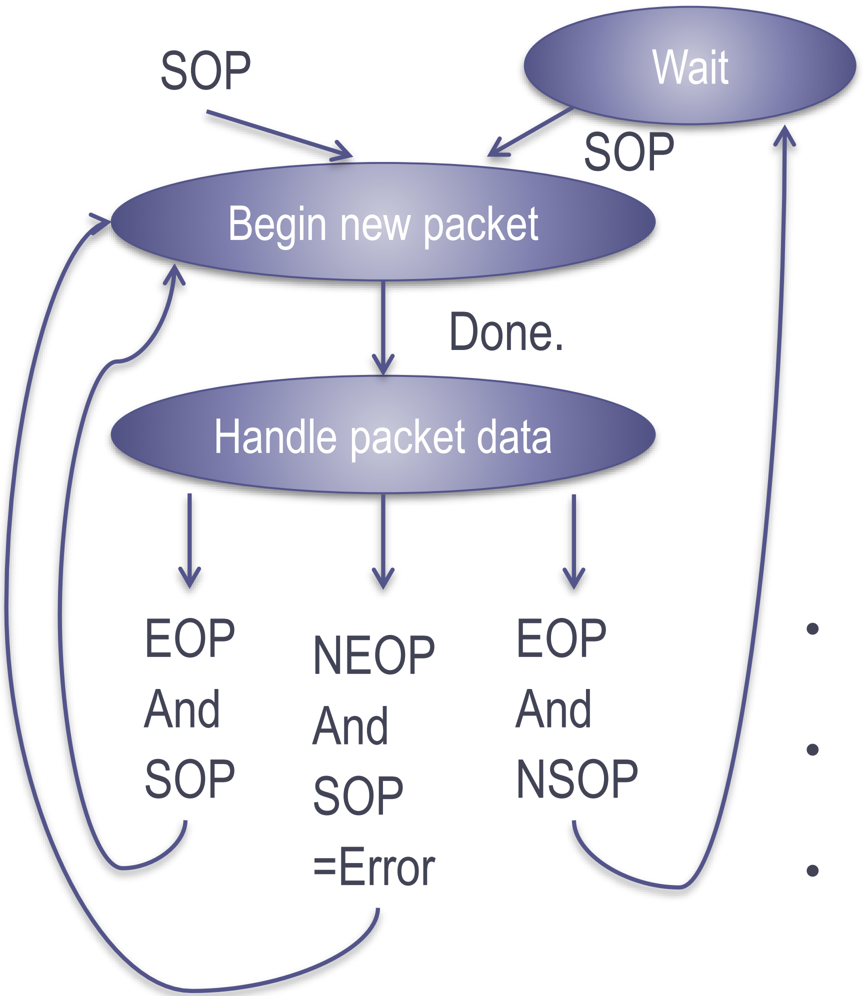
As with Xmit Train Packets, the actions show the interaction with the FPGA IP.

Note: "Send Data" includes sending null data, if necessary, before the trailer to ensure entire packet is a multiple of 32 bytes.

Flow Control:

- The diagram to the left shows operation with XON=1
- Of XON=0, data transmission stops within the flow control reaction time.

State diagram: Rcv Packets Consumer



Flow Control:

- If input buffer is within 900ns of overflow, set XON=0 (XOFF)
- If input buffer has less than 900ns of data loaded, set XON=1.

- In general, SOP always means start a new packet.
- EOP can occur with NSOP (no SOP), waiting for a SOP.
- However, SOP without an EOP is an error. For error recovery, the consumer starts a new packet with an SOP.

Documentation requirements

- RULE: All ODI devices SHALL document which ODI specifications they comply to.
- RULE: All ODI devices SHALL document the line rates and Interlaken BurstMax that are used.
- RULE: All ODI instruments SHALL document the maximum aggregate bandwidth required per port for operation at maximum speed in units of equivalent GB/sec.
- RULE: IF an ODI instrument has several modes requiring different aggregate bandwidth needs, then it must specify the aggregate bandwidth for each mode.
- RULE: All ODI non-instrument devices (e.g. storage, processors) SHALL document the maximum aggregate bandwidth it is capable of in equivalent GB/sec.
- RULE: An ODI device SHALL specify any other requirements in order to reach the quoted aggregate bandwidth
- OBSERVATION: For instruments that do not have resolutions on byte boundaries (8-bits, 16-bits, etc.), equivalent aggregate bandwidth in GB/sec is merely the Gb/sec divided by eight.