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OTN Over Packet Fabric Protocol (OFP) Implementation Agreement

IA # OIF-OFP-01.0

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Working Group: **Physical and Link Layer**

Title: OTN Over Packet Fabric Protocol (OFP) Implementation Agreement

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Abstract :: The OTN Over Packet Fabric Protocol Implementation Agreement defines the protocol that enables the switching of Optical Data Unit (ODUk/ODUflex) of the Optical Transport Network (OTN) hierarchy over a packet fabric within a Network Equipment (NE). This IA provides the segmentation and re-assembly functions required for timing transfer, packet loss detection and replacement, and packet delay variation compensation for the ODUk/ODUflex clients.

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4 Document Revision History

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Issue No.	Issue Date	Details of Change
OIF2011.052.00	January 2011	Draft inherited from OIF2010.348.05 with Editor's notes added
OIF2011.052.01	April 2011	Incorporated Editor's notes Updated ODUk/ODUflex rates breakpoints for Segmentation from ODU4.ts to Gbps. Added equations for generating D_{nom}, D_{Δ}, T_{adj}, T, B_{nom} Added Section on ODUflex resizing
OIF2011.052.02	July 2011	Incorporated OIF2011.131.01 into Section 4 Updated section on ODUflex resizing from OIF2011.232.00 to reflect decisions at the May 2011 ITU meeting. Fixed typos.
OIF2011.052.03	July 2011	Incorporated editorial comments provided by Ciena.
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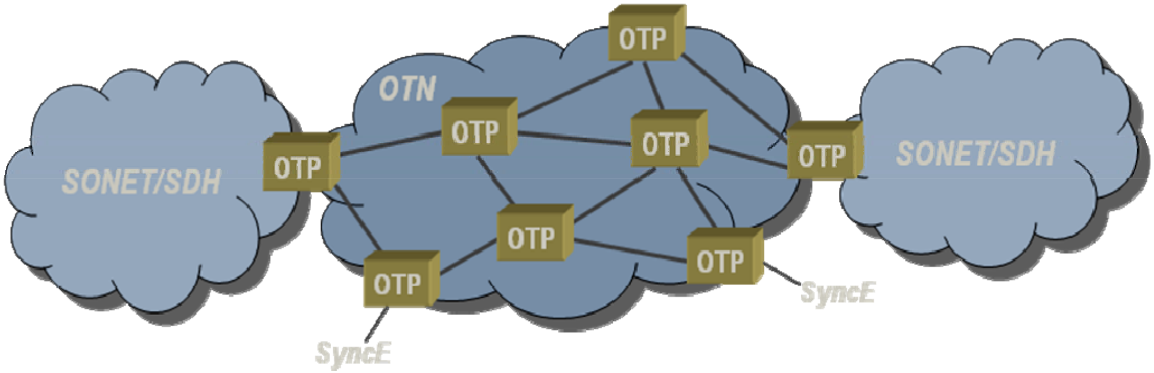
OIF2011.052.07	October 2011	Incorporated comments from Beijing Plenary.

5 Introduction

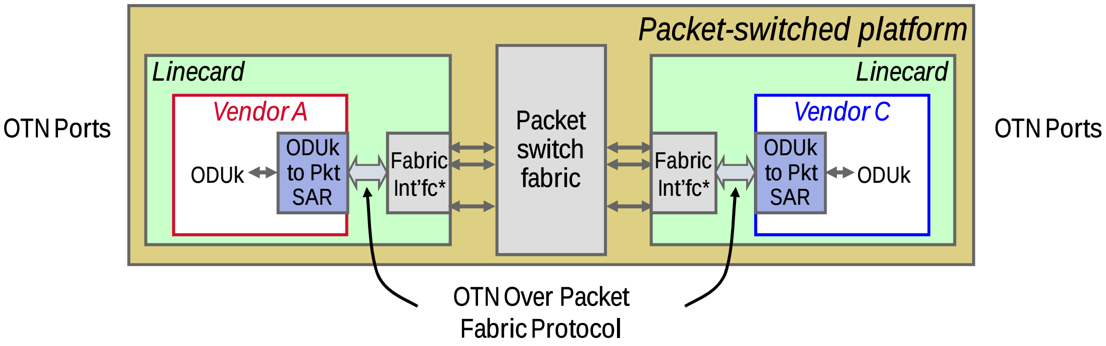
The optical communications network is evolving from a pure TDM (SONET/SDH) oriented network to a converged Packet (Ethernet) and TDM (OTN) network. Historically, Network Elements used separate fabrics, one for packet and another for TDM traffic. A single converged fabric is expected to be simpler, and consume less power and shelf real estate. As packet traffic is expected to form a significant portion, and in some cases the majority, of the traffic, it will be economically advantageous to build Network Elements using packet oriented switching fabrics and employ circuit emulation techniques to convert OTN client streams into packet format for switching by the packet fabric. Figure 1 shows a converged network with packet and OTN capable Optical Transport Platform (OTP) Network Elements.

Figure 1 Converged Packet and OTN Network



The OTN Over Packet Fabric Protocol (OFP) Implementation Agreement defines the protocols that enables the switching of ODUk/ODUflex streams arriving at an ingress linecard of a Network Element to an egress linecard over a packet oriented switching fabric. Protocols such as OIF SPI-S and Interlaken, already exist for connecting packet PHY devices to Packet fabric devices. This IA addresses the segmentation and re-assembly of ODUk/ODUflex stream such that frequency and phase of the ODUk/ODUflex stream is preserved. The ODUk/ODUflex segments can be switched over existing and future packet fabrics. Figure 2 shows the points within an OTP NE where the OTN Over Packet Fabric Protocol Implementation Agreement is applicable.

Figure 2 Converged Optical Transport Platform Network Element



The OTN Over Packet Fabric Protocol is based on the mapping of CBR clients into an ODUk and the multiplexing of Low Order ODUj into a High Order ODUk, as defined in ITU G.709. In those definitions, a variable amount of CBR client or ODUj data is mapped into each ODUk frame, which has a fixed period. The variation in the amount of data encodes the rate of the CBR client or the ODUj stream carried within the ODUk. This technique, commonly referred to in OTN standards, is called justification and is re-used here as the technique for encoding the timing information of the ODUk/ODUflex switched across the packet fabric. The rate of the ODUk client is encoded by varying the amount of data in each packet, where the packets are constructed over a fixed time period.

5.1 OTN Over Packet Fabric Protocol Requirements

The following are the set of requirements that must be met by the OTN Over Packet Fabric Protocol in order to support the transport of ODUk/ODUflex clients across network elements and packet switching fabrics with a variety of implementation characteristics. The OTN Over Packet Fabric Protocol shall

- Provide a mechanism for transferring the timing information of ODUk/ODUflex client signals across a packet fabric such that ITU-T Recommendation G..8251 ODCr and ODCp timing specifications are still met without reduction in the maximum number of NEs allowed by the G.8251 Hypothetical Reference Model,
- Provide a mechanism for transferring the timing information of ODUk/ODUflex client signals across a packet fabric that is agnostic to fabric latency and latency variations,
  - Support packet fabric implementations with a maximum fabric latency of up to 100µs and a maximum latency variation of up to 50µs.
  - Provides a mechanism to compensate the packet fabric latency to a configurable value (max fabric latency <= config value <= 100µs) with a resolution of better than 5ns.
- Provide a mechanism to signal the status of the ODUk/ODUflex client (Status = No Defect, Signal Degrade, Signal Fail),

- Provide a mechanism to protect against a re-frame of the ODUk/ODUflex stream in the event of single packet loss by the packet fabric
- Support the use of a common reference 311.04MHz clock, that is phase-locked to a common timestamp synchronization pulse of 8kHz,
- Support packet fabrics with a variety of internal packet sizes from 128 to 512 bytes and ODUk/ODUflex packetization that allows optimal use of the packet fabric bandwidth, and
- Support for interoperable receiver and transmitter implementations.

Support of packet fabrics that deliver packets out of order is NOT required. Ordered delivery of packets across the packet fabric is the responsibility of the packet fabric itself.

5.2 Objectives

The following are additional objectives that may be met by the OTN Over Packet Fabric Protocol in order to support the transport of ODUk/ODUflex clients across network elements and packet switching fabrics with a variety of implementation characteristics. The OTN Over Packet Fabric Protocol may

- Provide a mechanism to protect against a re-frame of the ODUk/ODUflex stream in the event of double (consecutive) packet loss by the packet fabric.

6 Segmentation and Reassembly Models

6.1 Introduction

In the context of the OTN Over Packet Fabric Protocol, a Network Element (See Figure 3 below) consists of ingress OTN functions, ingress SAR functions, a packet fabric, egress SAR functions and egress OTN functions. A common reference clock (REFCLK) and a synchronization pulse (SYNC) must be distributed to all ingress and egress SAR functions. REFCLK and SYNC must be derived from a common timing reference and are phase locked to each other. The ingress OTN functions consist of an OTUk framer, which terminates the OTUk overhead, performs Forward Error Correction (FEC) and outputs the corresponding High-Order ODUk stream. There may also be one or more ODTUjk De-multiplexer stages, which extract Low-Order ODUj/ODUflex clients from the High-Order ODUk carrier stream. The High-Order or Low-Order streams are segmented into packets by the ingress SAR functions and forwarded to a packet fabric. The packet fabric switches the traffic, which is then reassembled by the egress SAR functions back into ODU data streams that are processed by the OTN egress functions. In the OTN egress functions, High-Order ODUk streams can be adapted to become an OTUk stream with the addition of OTUk overhead and FEC checksum bytes. Low-Order ODUj/ODUflex streams are multiplexed into a High-Order ODUk streams. The entire system must preserve the timing integrity of the ODU streams from ingress to egress.

Figure 3 OTN Over Packet Fabric Network Element Model

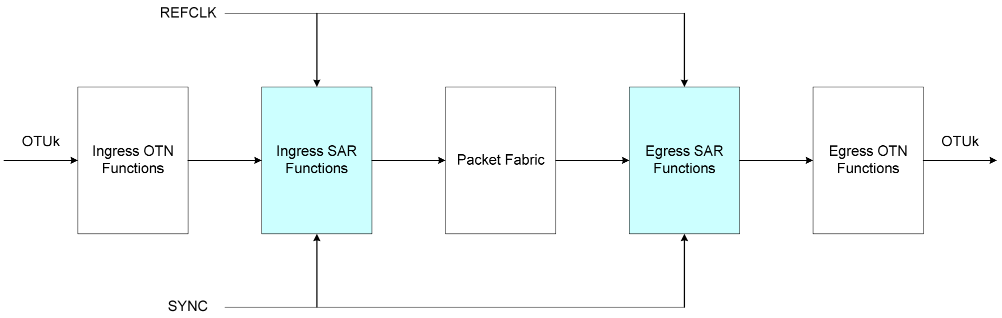


Table 1 Global Signals

Signal	Description
REFCLK	311.04MHz SAR reference clock. Used by ingress SAR functions to measure the rate of the incoming ODUk/ODUflex. Used by egress SAR functions as reference to generate outgoing ODUk/ODUflex streams. The SAR reference clock may be derived from other system reference rates, such as a 155.52MHz clock, which must remain phase-locked with the SYNC signal.
SYNC	8kHz synchronization pulse. Used by ingress and egress SAR functions to synchronize timestamping used to compensate for packet latency variation.

	SYNC is phase-locked to REFCLK. The SAR synchronization pulse may be derived from other system level synchronization pulse reference rates, such as 2kHz or 4kHz signals.

6.1.1 Ingress SAR Functions

Figure 4 and Figure 5 below shows the functional blocks of the Ingress SAR functions in conjunction with a representative set of ingress OTN functions for cases of with and without ODTU multiplexing. These are logical representations only and are not intended to limit implementation. Blocks directly related to OTN Over Packet Fabric are high-lighted in blue.

Figure 4 Ingress Functional Blocks (Regenerator)

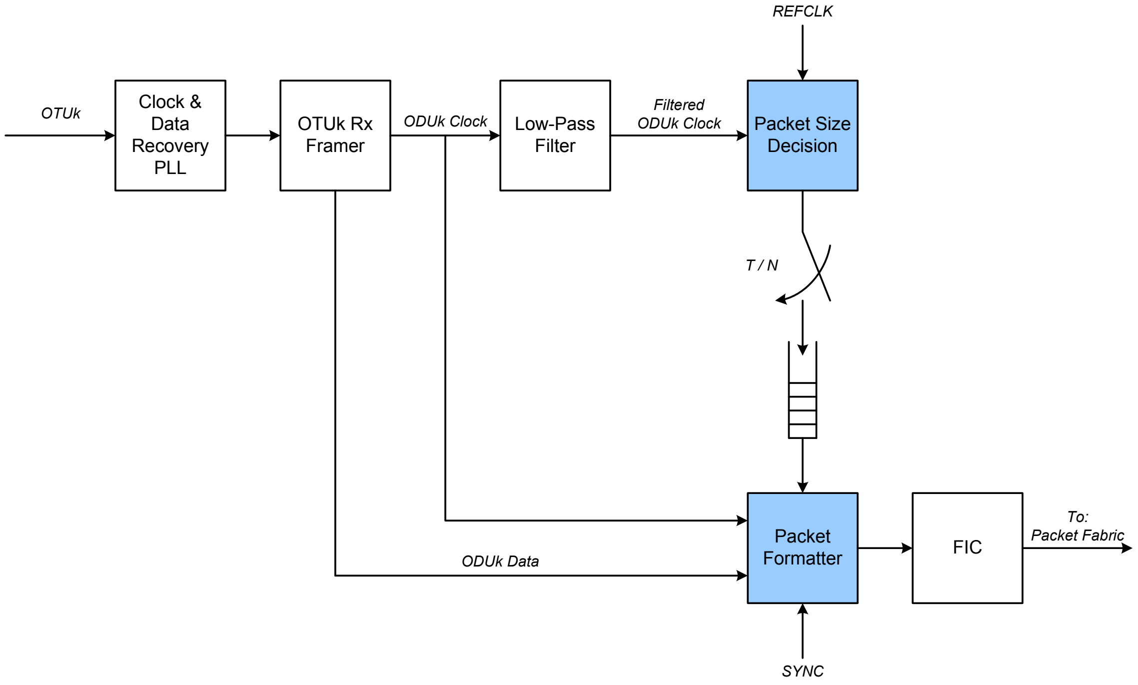
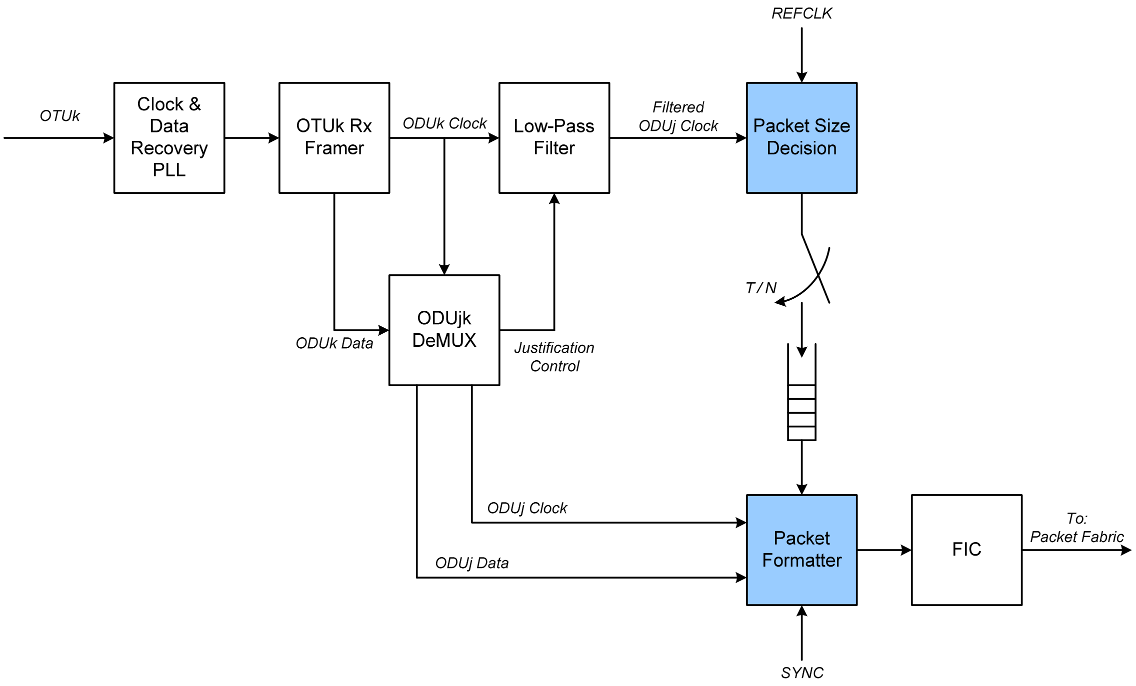


Figure 5 Ingress Functional Blocks (ODUk to ODUj/ODUflex Demultiplexing)



For either of the two cases shown in Figure 4 and Figure 5 above, the OTUk is recovered and processed. In the regenerator case, the ODUk clock is low-pass filtered, while in the multiplexed case, the ODUj/ODUflex is extracted and low pass-filtered, before being forwarded to the Packet Size Decision (PSD) function. The low-pass filter represents the standard 300Hz bandwidth desynchronizer filter specified by the OTN standards. The ODUk or ODUj/ODUflex data is forwarded to the Packet Formatter (PF) function.

The PSD function makes packet size decisions related to the rate of the filtered ODUk or ODUj/ODUflex clock. Packet size decisions are generated at a rate of N decisions every T cycles of the SAR reference clock, (e.g., 1 decision every 237 cycles or 32 decisions every 943 cycles). The Packet Formatter (PF) constructs packets with sizes as directed by the PSD. Therefore, packets are constructed at an average rate of one packet every T/N cycles of the SAR reference clock and would have an average size of (ODUk/ODUflex Rate * T) / (8 * REFCLK * N) bytes. Generating a packet size decision every T/N cycles may be impractical for some implementations. Thus, it may be desirable to generate an aggregate packet size decision every T cycles, and subsequently segment it into N individual packet size decisions. Table 2 below lists the recommended Segmentation Ratio (N) values for various ODUk/ODUflex (F_{ODU}) rates.

Table 2 Segmentation Ratio (N) for Various ODUk/ODUflex Rates and Packet Fabric Classes

ODUk/ODUflex Rate	N		
	128-byte fabric	256-byte fabric	512-byte fabric
ODU0, ODU1	1	1	1
ODU2, ODU1e, ODU2e, ODU1f, ODU2f	1	1	1
ODU3, ODU3e1, ODU3e2	8	4	2
ODU4	16	8	4
F_{ODU} <= 11.0 Gbps	1	1	1
F_{ODU} <= 42.0 Gbps	8	4	2
F_{ODU} <= 105.0 Gbps	16	8	4
F_{ODU} <= 225.0 Gbps (informative)	(32)	(16)	(8)
F_{ODU} <= 425.0 Gbps (informative)	(64)	(32)	(16)
F_{ODU} <= 1100.0 Gbps (informative)	(128)	(64)	(32)

Packet size decisions are equivalent to a common transport function known as justification. Traditional justification mechanisms can produce very low frequency phase discontinuities in the client signal timing that are difficult to filter. A well known technique for generating justification (or packet size) decisions that minimizes this problem is a Sigma-Delta Modulator, which makes justification decisions very frequently in order to provide frequency shaping of the phase discontinuities. This technique shall be utilized in the PSD function for generating aggregate packet size decisions to improve timing transfer performance. The individual packet size decisions are written into a size decision FIFO.

The Packet Formatter, under the control of the individual packet size decisions read from the size decision FIFO, produces data packets of the proper size. It then adds the appropriate packet overhead required by the OTN Over Packet Fabric Protocol. This overhead includes a timestamp which is determined by a counter that increments by one at each REFCLK cycle and resets to zero on the rising edge of the SYNC pulse. This counter has a modulo of 38880. The timestamp is used by the egress SAR function to compensate for packet latency variations. Other overhead includes bits assigned for error resilience, particularly packet loss, and reporting of client signal status from ingress to egress functions.

The PSD function is governed by the equations in Table 3 below. A list of variable with a brief description is available in Appendix A. A compliant device shall support N, T, D and B generated from Table 2 and Table 3. A device may optionally support T, D and B resulting from a T_{adj} that is 1 higher than the value given by Eqn 8.

Table 3 Governing Equations of PSD

Equation #	Equation
Eqn 1	$D_{max} = B_{max} * N$
Eqn 2	$BpRC = F_{ODU} / (8 * F_{REF})$
Eqn	$T_{max} = INT(D_{max} / BpRC)$
Eqn 4	$D_{Tmax} = Round(T_{max} * BpRC)$
Eqn 5	$\varepsilon_{wc} = 0.5$
Eqn 6	$\varepsilon_{ppm} = D_{max} * (PPM_{ref} + PPM_{ODU}) * 10^{-6}$
Eqn 7	$D_{\Delta} = 1$, when $N < 4$ $D_{\Delta} = RoundUp\ (\ 2*(\varepsilon_{wc}+\varepsilon_{ppm})\ )$, when $N >= 4$
Eqn 8	$T_{adj} = RoundUp\ (\ [D_{Tmax} + D_{\Delta} - D_{max}] / BpRC\ )$, when $[D_{Tmax} + D_{\Delta} - D_{max}] > 0$ $T_{adj} = 0$, when $[D_{Tmax} + D_{\Delta} - D_{max}] <= 0$
Eqn 9	$T = T_{max} - T_{adj}$
Eqn 10	$D_{avg} = T * BpRC$
Eqn 11	$D_{nom} = Round\ (D_{avg})$
Eqn 12	$\varepsilon_{nom} = D_{avg} - D_{nom}$
Eqn 13	$D = \{D_{nom}-D_{\Delta}, D_{nom}, D_{nom}+D_{\Delta}\}$
Eqn 14	$B_{nom} = Min\ [Round\ (D_{avg} /N), B_{max}-1]$
Eqn 15	$B = \{B_{nom}-1, B_{nom}, B_{nom}+1\}$

An aggregate packet size decision (D) is generated every T cycles of the 311.04MHz reference clock (REFCLK). During the period of (T/311.04MHz), the incoming ODUk/ODUflex stream is expected to deliver an average of $D_{avg} = (F_{ODU} * T) / (311.04MHz*8) = D_{nom}+\varepsilon_{nom}$ bytes, where D_{nom} is the nearest integer, and ε_{nom} is a fractional offset. Note that ε_{nom} can have a positive or a negative value. The actual epsilon (ε_{act}) is the sum of ε_{nom}, the current ppm offset of the ODUk/ODUflex stream (ε_{ppm}), and jitter/wander (ε_j).

$$\varepsilon_{act} = \varepsilon_{nom} + \varepsilon_{ppm} + \varepsilon_j$$

The nominal aggregate packet size decision (D_{nom}) of the ODUk is the integer nearest to D_{avg}. ε_{act} is encoded by varying the size decision by $+D_{\Delta}$, 0, or $-D_{\Delta}$. For example, if $D_{nom} = 1280$ and $\varepsilon_{act}=0.33$, the PSD may generate size decisions D = 1280, 1281, 1280, 1279, 1281, 1281, 1280, 1280, 1279, … such that the sequence averages to 1280.33. Given the very high rate of decision generation, the amount of phase contribution by jitter/wander is negligibly small. Thus, ε_j can be treated as being 0.

An incoming ODUflex stream may have a frequency offset of up to ±100ppm. When coupled with the local reference clock offset of ±20ppm, the total effective offset is ±120ppm. At higher ODUflex rates, the large ε_{ppm} can cause ε_{act} to be larger than 1. The variance in D must be sufficiently large to span the range of ε_{act}. For good Sigma-Delta performance, the decision variance (D_{Δ}) is set to $2*(\varepsilon_{ppm} + \varepsilon_{wc})$, rounded up to the next integer for N>=4. For N<4, it is set to 1 so that every decision can be expressed in exactly N packets with payloads of $B_{nom} \pm 1$ bytes. ε_{wc} is the worst case fractional portion of ε_{nom}, measured from the nearest integer. Thus, $\varepsilon_{wc} = 0.5$.

Finally, the PSD segments the aggregate packet size decisions into N individual packet size decisions. Each packet shall have a size of B_{nom} ± 1 bytes. The sum of the individual packet sizes shall encode the aggregate packet size decision (D) losslessly. Packets shall be generated at an average rate of T/N cycles of the 311.04MHz system reference clock.

The ODUk data is sent to the Packet Formatter (PF). The Packet Formatter reads individual packet size decisions (B) from the Size Decision FIFO and formats the ODUk data into packets of the directed size. The Packet Formatter maintains a timestamp counter which increments at every cycle of the 311.04MHz reference clock (REFCLK). The counter modulo is 38800. Thus, the counter period is 125µs. The timestamp counter is initialized to 0 by the 8kHz frame pulse (SYNC). In order to allow for small phase variances between the 311.04MHz reference clock and the 8kHz frame pulse, the counter will not re-initialize to 0 if the current count value is within ±8 of 0, at the time the frame pulse is detected. The value of the timestamp counter at the time of creation of each packet is captured in the overhead bytes of the packet.

Table 4 below shows the supported range of B_{max} for 128-byte, 256-byte and 512-byte class of packet fabrics. The range of supported B_{max} provides a range of 0 to 12 bytes of user specific and fabric overhead and 4 bytes of OFP overhead.

Table 4 Supported B_{max} Limits

Packet Fabric Class	Minimum B_{max}	Maximum B_{max}
128-byte	112	124
256-byte	240	252
512-byte	496	508

The Fabric Interface Chip (FIC) takes in packets constructed by the Packet Formatter over an industry standard packet bus, such as OIF SPI-S, or Interlaken, and adds fabric specific overhead bytes. The packets are sent to the Core Fabric for switching to destination egress line cards. In the case of hybrid ingress line cards serving both OTN and packet (eg., Ethernet) clients, the FIC may segment the packet traffic into smaller segments for transfer over the fabric.

6.1.2 Egress SAR Functions

Figure 6 and Figure 7 below show the functional blocks of two kinds of egress functions, a regenerator configuration and an ODUj/ODUflex to ODUk multiplexing configuration. They are logical representations only and are not intended to limit implementation. Blocks directly related to OTN Over Packet Fabric are high-lighted in blue.

Figure 6 Egress Functional Blocks (Regenerator)

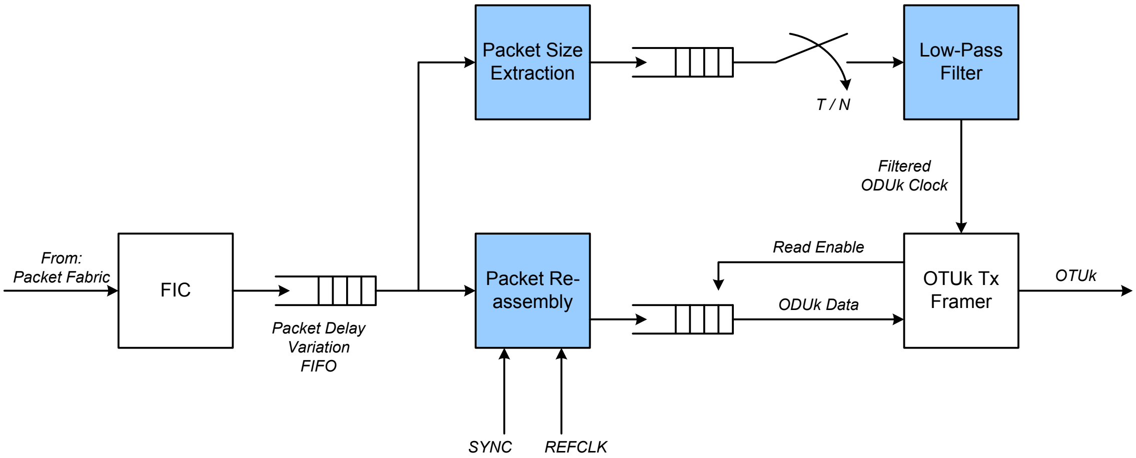
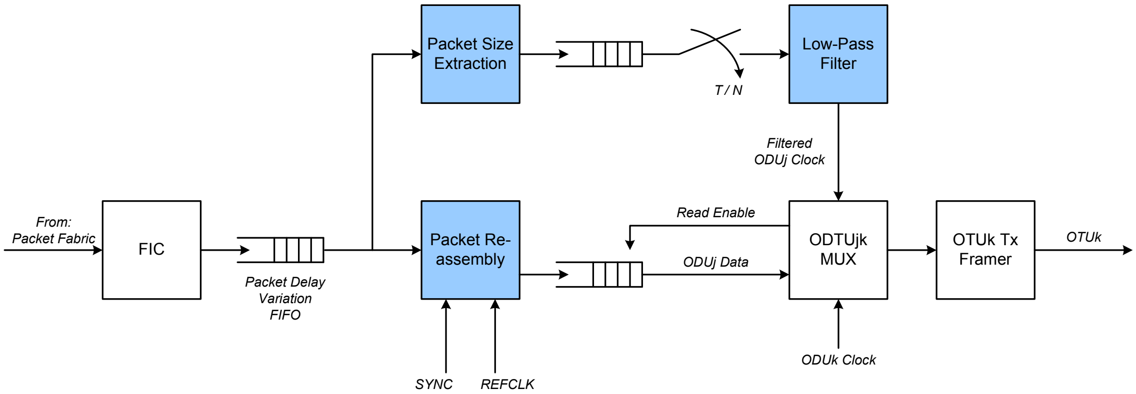


Figure 7 Egress Functional Blocks (ODUj/ODUflex to ODUk Multiplexing)



ODUk packets are delivered by the packet fabric. The Packet Re-assembly (PR) function removes the OTN Over Packet Fabric Protocol header bytes and converts the packet stream into a contiguous serial ODUk/ODUflex stream. The Packet Size Extraction (PSE) function extracts the size of each packet. The packet sizes are loaded into a FIFO and read out at an average rate of once every T/N cycles of the reference clock. The resulting clock information is low-pass filtered, removing the noise generated by the ingress noise shaper. By metering the rate of packet size updates to the filter at a precise period, fabric packet delay variations have no impact on jitter and wander of the transmitter ODUk/ODUflex.

The egress SAR function maintains a timestamp counter which increments at every cycle of the reference clock. The timestamp counter is initialized by the SYNC pulse. The egress SAR function also provides a packet delay variation FIFO for each ODUk/ODUflex stream. This FIFO buffers some amount of data so that the transmit ODUk/ODUflex stream is not interrupted by packet delay variations in the fabric. After reset, the depth of the FIFO is initialized by suspending the read operation until the packet at the head of the FIFO is of a configured age, i.e., suspend reading until (timestamp counter – packet timestamp) > configured value. The FIFO initialization process may be used to ensure that all ODUk/ODUflex streams have the same latency through the Network Element regardless of the packet delay variations in the fabric.

The output data stream and its filtered clock are then processed by the OTN functions. For a regenerator application this information is passed to the egress OTN framer. If ODUj/ODUflex multiplexing is provided, then the information is utilized by the multiplexer and then the multiplexed signal is processed by the OTN framer.

7 Packet Format

The packet format of the OTN Over Packet Fabric Protocol is shown in Figure 8 below. Each packet contains an optional 0 to 12 byte User Specific and Fabric Overhead field, 4 bytes of OTN Over Packet Fabric overhead field, and an ODUk/ODUflex Payload field that is B_{nom}±1 byte. B_{nom} is software configurable to best match the packet size characteristics of the packet switching fabric. The definitions of the fields are listed in Table 5. The definition of the User Specific and Fabric Overhead field is outside the scope of this IA.

Figure 8 Packet Format

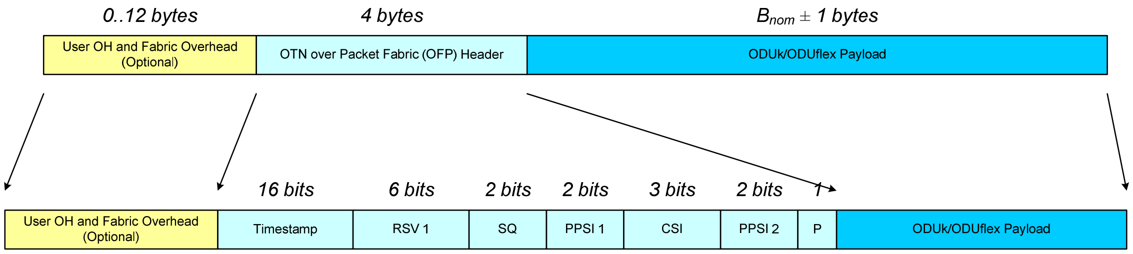


Table 5 Packet Fields

Field	Description
Timestamp	Timestamp is a 16-bit count that records the time of creation of the packet relative to the system 8kHz frame pulse (SYNC), in steps of 311.04MHz system reference clock (REFCLK) cycles. The range of Timestamp is 0 to 38879.
RSV 1	RSV 1 is a 6-bit field that is reserved for future standardization. Eg., RSV 1 can be combined with SQ to form a larger sequence number field to support packet fabrics that may deliver packets out of order.
SQ	SQ is a 2-bit sequence number used to detect packets dropped by the switching fabric due to, for example, congestion or bit errors. SQ is a binary counting number that increments with every packet, per ODUk/ODUflex.
PPSI 1	PPSI 1 is a 2-bit field that records the size of the previous packet. When the previous packet is dropped by the switching fabric, the egress linecard can use PPSI 1 to construct a replacement packet of the indicated size to avoid changing the frame alignment of the ODUk/ODUflex stream. PPSI 1 = ‘b00 : Previous packet size is B_{nom} bytes PPSI 1 = ‘b01 : Previous packet size is B_{nom}+1 bytes PPSI 1 = ‘b10 : Reserved PPSI 1 = ‘b11 : Previous packet size is B_{nom}-1 bytes PPSI 1 is a 2’s-complement encoding of (-1, 0, +1).
CSI	CSI is an optional 3-bit Client Status Indication field that may be used for fast APS applications. CSI carries the status of the ODUk/ODUflex stream. CSI = ‘b000 : Forces the switching fabric to select this ODUk/ODUflex even if the alternate stream is in the No Defects state. CSI = ‘b001 : No Defects detected

	CSI = ‘b010 : Signal Degrade detected CSI = ‘b011 : Signal Fail detected CSI = ‘b100 : Server Signal Fail detected CSI = ‘b111 : Forces the switching fabric to not select this ODUk/ODUflex regardless of the state of the alternate stream. CSI = ‘b101 and ‘b110 : Reserved Implementation of CSI is optional. When not used, the CSI field is set to ‘b001.
PPSI 2	PPSI 2 is an optional 2-bit field that records the size of the previous-previous packet. When two consecutive packets are dropped by the switching fabric, the egress linecard can use PPSI 1 and PPSI 2 to construct two replacement packets of the indicated sizes to avoid changing the frame alignment of the ODUk/ODUflex stream. PPSI 2 = ‘b00 : Previous-previous packet size is B_{nom} bytes PPSI 2 = ‘b01 : Previous-previous packet size is B_{nom}+1 bytes PPSI 2 = ‘b10 : Reserved PPSI 2 = ‘b11 : Previous-previous packet size is B_{nom}-1 bytes PPSI 2 is a 2’s-complement encoding of (-1, 0, +1). Implementation of PPSI 2 is optional. When not used, the PPSI 2 field is set to ‘b00.
P	P is a 1-bit odd parity field computed over the entire OTN Over Packet Fabric Header (from Timestamp to P)
User Specific and Fabirc OH	User Specific and Fabric Overhead is an optional 0-12 byte field reserved for user proprietary data and fabric overhead. The specification of this field is outside the scope of this IA.
Payload	The Payload field carries B_{nom}-1, B_{nom}, or B_{nom}+1 bytes of an ODUk/ODUflex stream.

The bit ordering of ODUk/ODUflex bits in ITU G.709 and in this IA are shown in Figure 9 below. The most significant bit is transmitted first in G.709 and is assigned bit 1. The least significant bit is transmitted last and is assigned bit 8. The corresponding bits within a payload byte are bits [7] and [0], respectively. ODUk/ODUflex octets are inserted into the Payload field in the order of transmission.

Figure 9 Bit Ordering Relationship to OTN Octets

OTN Octet	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
	msb							*lsb*
OPF Byte	*[7]*	*[6]*	*[5]*	*[4]*	*[3]*	*[2]*	*[1]*	*[0]*

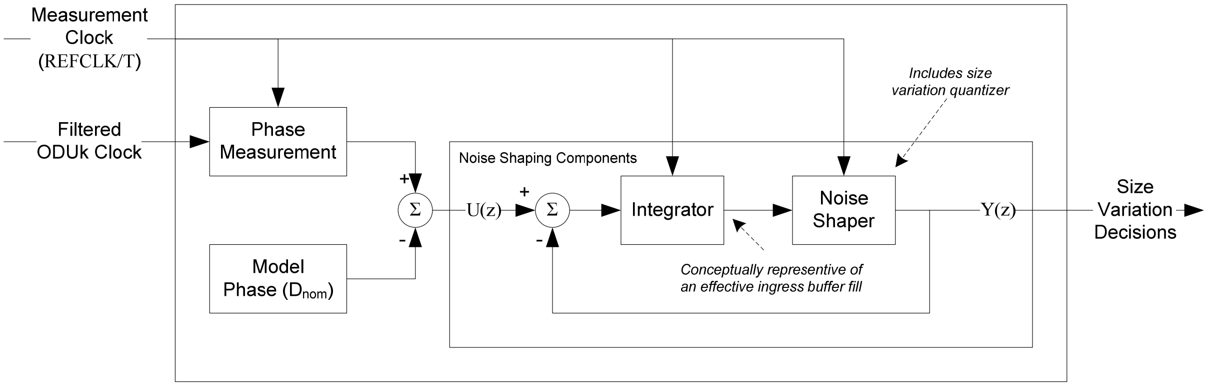
8 Ingress Noise Shaping and Egress Filtering Functions

The required noise performance of the SAR implementation is achieved through noise shaping of aggregate packet size decisions generated by the ingress SAR function (Figure 4 and Figure 5) coupled with the appropriate filtering of those decisions by the egress SAR function (Figure 6 and Figure 7).

8.1 Packet Size Decision Model

The ingress aggregate packet size decisions are generated as a result of the difference between the incoming recovered ODUk/flex clock and the clock corresponding to a model data rate. The model data rate is D_{nom} bytes per measurement interval (T). This is illustrated in Figure 10.

Figure 10 Packet Size Decision Variance High Level Diagram

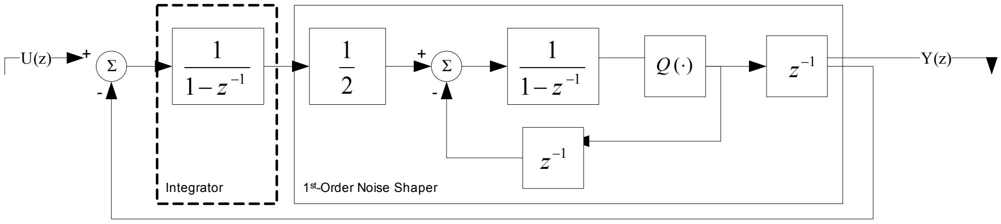


The OTN Over Packet Fabric Protocol uses packet size variations to signal the rate of the ODUk/ODUflex from the ingress to the egress SAR function. Conceptually, the size variation decision process monitors the fill level of an effective ingress data buffer and, once the buffer fill crosses a predetermined threshold, causes the decisions (D) to be increased or decreased in size. Each size variation (variation in data transmitted per measurement interval from its nominal value, Dnom) creates a phase discontinuity of DΔ bytes (±8UI * DΔ) per measurement interval (T reference clock cycles). The generation of the size variations produces quantization noise which must be shaped in order to eliminate low frequency (and thus hard to filter) noise content. The noise transfer function coupled with an egress filter function are required to provide the timing transfer jitter and wander performance for OTN signals carried over the packet fabric.

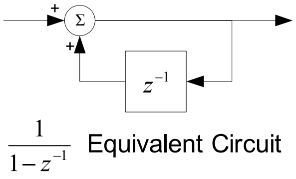
8.2 Ingress Noise Shaping

To minimize the effect of the noise generated by the decisions (D), noise shaping at the ingress SAR function shall be provided. The characteristics of the noise shaping are determined by the noise shaping components of the packet size decision model illustrated in Figure 10 above. The derivation of the required noise shaping transfer function is based on the noise shaping components shown in Figure 11a.

Figure 11 Shaping Components and Model



(a)

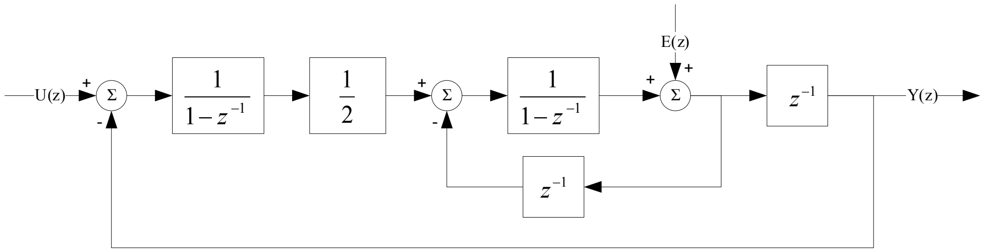


(b)

$$Q(x) = \begin{cases} D_\Delta & x \geq D_\Delta / 2 \\ 0 & -D_\Delta / 2 < x < D_\Delta / 2 \\ -D_\Delta & x \leq -D_\Delta / 2 \end{cases}$$

D_Δ = Variance in decision (bytes)

(c)

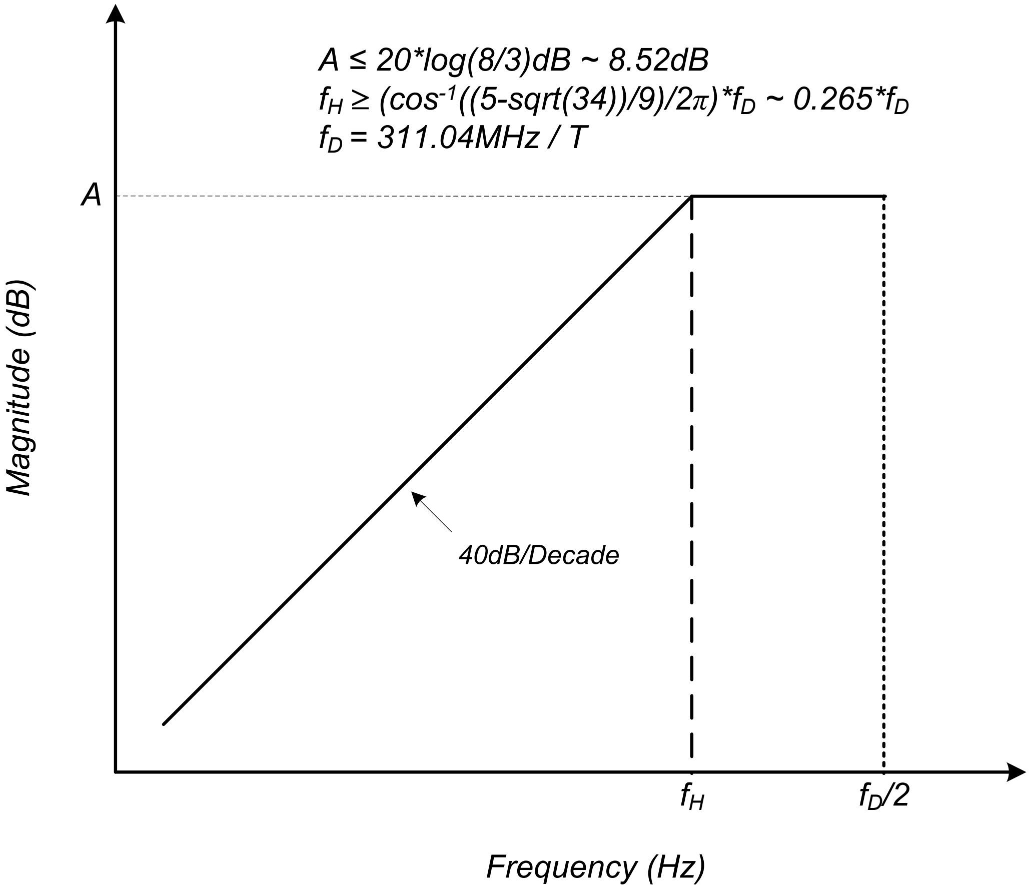


(d)

The noise shaping components consist of an integrator, which is represented in Figure 11b, and a 1st-order noise shaper that includes the packet size decision quantizer. The quantizer function is defined by the relationship given in Figure 11c. For the purposes of determining the noise transfer function the quantizer is replaced with an error input and summation node, where the error is equivalent to the function *Q(x)-x*. This is shown in Figure 11d.

The packet size decision noise transfer function, as derived from Figure 11d, shall be a second order high-pass filter. (Note: The second order response results from the closing of the feedback loop prior to the integrator.) The response of the noise shaper for justifications ($-D_\Delta$, 0, $+D_\Delta$) shall lie below the mask provided in Figure 12.

Figure 12 Noise Transfer Function Mask

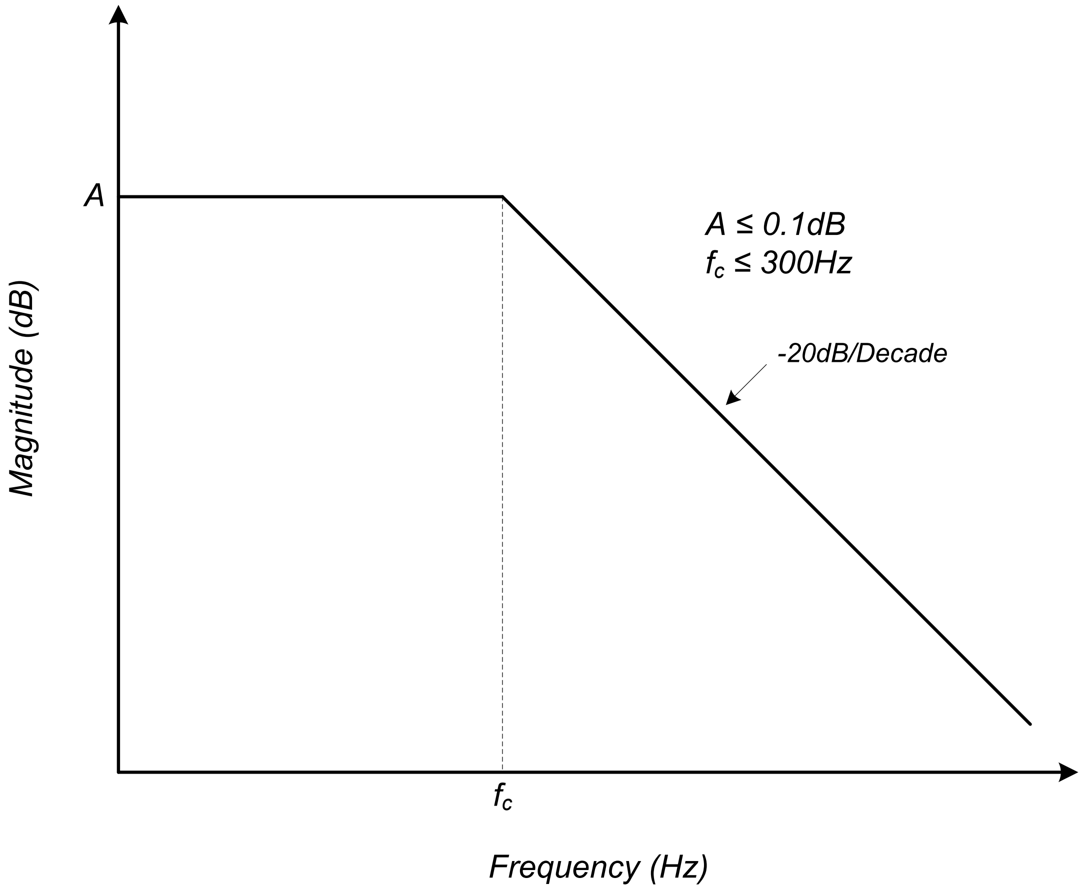


The implementation of Figure 11 used to derive the noise transfer is not in itself required, only adherence to the resulting noise transfer function. Any implementation meeting the requirements of the mask of Figure 12 is permissible.

8.3 Egress Filtering

The low pass filter in the egress SAR function is used to remove the noise components produced by the ingress noise shaper. The egress filtering function as shown in Figures 6 and 7 represents the filtering of the individual packet size decisions for the purpose of recovering the timing of the associated ODUk/ODUflex carried across the fabric. This function would typically be provided by some form of phase locked loop whose input phase is the nominal clock plus the phase information provided by the justification decisions. The overall response of the phase locked loop is second order and must have a corner frequency (f_c) of ≤ 300 Hz with less than 0.1 dB of peaking as shown in Figure 13.

Figure 13 Egress Filter Function Mask



9 ODUflex Resizing

The resizing of ODUflex(GFP) streams is specified in ITU G.7044. When the ODUflex is being resized, the rate of the ODUflex may change by a factor of up to 80X. This amount of change is outside the range addressable by $D_{nom} \pm D_{\Delta}$. However, ODUflex(GFP) streams are not used to carry timing, especially during the resizing operation. Thus, the precise rate and phase signaling capability of variable packet sizing is not required. The ramp in the speed of the ODUflex is specified to be at a fixed rate of 512Mbps/s. The following scheme is used to signal the ODUflex rate during resizing :

1. During "GMP Special Mode" the Ingress SAR function does not need to generate packet size decisions that tracks the rate of the ODUflex, as they will be ignored by the Egress SAR function. Although the individual packet sizes are arbitrary, they must still fall within the range of $B_{nom}\pm1$.

2. During "GMP Special Mode" the Egress SAR function does not use packet size variations to determine the rate of the ODUflex. Instead, the Egress SAR function compares the Timestamp field in the OFP Header to the current Timestamp counter value to determine the age of the packet. The rate of the ODUflex is increased if the filtered age is older than the configurable target and decreased if the filtered age is younger.

3. Upon being signaled by BWR_IND field in the OPUflex overhead to begin, the Egress SAR function changes the rate of the ODUflex at the nominal rate of 512Mbps/s, subject to biasing by filtered packet age. Ramping stops when so signaled by BWR_IND or when the ODUflex has reached the configured final rate. During the ramp, the age-based adjustment process depicted above remains in effect to compensate for ppm offsets between the reference clock of the upstream Network Elements and the local reference clock.

4. At any time during "GMP Special Mode", the Ingress and Egress SAR functions can be re-configured to the final ODUflex rate. The Network Element exits "GMP Special Mode" when the upstream node has exited "GMP Special Mode", the SAR functions have been re-configured and both the Ingress and Egress SAR functions have stabilized to the final ODUflex rate.

5. Upon exiting "GMP Special Mode", variable packet size is again used to signal the rate of the ODUflex between the Ingress and Egress SAR functions.

10 Summary

The OTN Over Packet Fabric Protocol Implementation Agreement defines the protocol that enables the switching of Optical Data Unit (ODUk/ODUflex) of the Optical Transport Network (OTN) hierarchy over a packet fabric within a Network Equipment (NE). This IA provides the segmentation and re-assembly functions required for timing transfer, packet loss detection and replacement, and packet delay variation compensation for the ODUk/ODUflex clients.

11 Glossary

12 References

12.1 Normative references

[1] International Telecommunication Union, ITU-T G.709, “Interfaces for Optical transport Network”, December 2009.

[2] International Telecommunication Union, ITU-T G.7044, Q11, SG15, WP3, “WD33r6, Hitless Adjustment of ODUflex(GFP) (HAO)”, September 2011

12.2 Informative references

13 Appendix A: List of Variables

This informative appendix lists the variables used in this Implementation Agreement.

Variable	Description	Value
F_{ref}	SAR reference clock frequency	311.04 MHz
F_{sync}	Timestamp synchronization pulse frequency	8 kHz
F_{ODU}	Rate of ODUk/ODUflex client in bits/sec (bps)	
PPM_{ref}	PPM offset of REFCLK	20
PPM_{ODU}	PPM offset of ODUk/ODUflex	20 .. 100
BpRC	Number of ODUk/ODUflex bytes received in 1 SAR reference clock period.	
B_{nom}	Nominal number of ODUk/ODUflex client bytes per packet	
B_{max}	Maximum number of ODUk/ODUflex client bytes per packet supported by the fabric. B_{max} = Fabric cell size – Overhead bytes	
N	Segmentation Ratio. Number of $B_{nom}\pm1$ packets generated by each Decision.	
T_{max}	Integer portion of the number of REFCLK cycles needed to receive N* B_{max} bytes from a nominal ODUk/ODUflex client.	
T_{adj}	A reduction in T_{max} to ensure Decision is at or below D_{max}.	
T	Decision period, in integer number of REFCLK cycles. $T = T_{max} - T_{adj}$	
D_{avg}	Average number of ODUk/ODUflex client bytes in a decision period (T). D_{avg} is a floating point value.	
D_{nom}	Nominal number of ODUk/ODUflex client bytes per decision	
D_{Δ}	Variance in Decision, in number of ODUk/ODUflex client bytes per decision.	
D	Decision, in number of ODUk/ODUflex client bytes. D has value $[D_{nom}- D_{\Delta}, D_{nom}, D_{max}+ D_{\Delta}]$. Each decision is segmented into N packets, each carrying $B_{nom}\pm1$ ODUk/ODUflex client bytes.	
ε_{nom}	Nominal Epsilon of an ODUk/ODUflex client. $\varepsilon_{nom} = D_{avg} - \mathrm{Round}(D_{avg})$	
ε_{wc}	Worst Case nominal Epsilon	0.5
ε_{ppm}	Variance in the number of ODUk/ODUflex client bytes in each decision period due to clock offsets. $\varepsilon_{ppm} = D_{nom}$ * (Max ppm offset of ODUk/ODUflex client rate + Max ppm offset of REFCLK)	
ε_{j}	Variance in the number of ODUk/ODUflex client bytes in each decision period due to phase noise. ε_{j} is negligibly small.	0.0
ε_{act}	Actual Epsilon. $\varepsilon_{act} = \varepsilon_{nom} + \varepsilon_{ppm} + \varepsilon_{j}$	

14 Appendix B: Noise Shaping Performance Validation

The operation of the noise shaping functions defined in Section 8 is an important consideration for interoperability. Since the ingress and egress functions may exist on different devices, potentially from different vendors, it is important to be able to validate the noise shaping independent of other factors. It is important to consider methods by which this might be accomplished.

The noise transfer information is incorporated in the outgoing packet size decisions.

$$Y(z)_{noise} = f[E(z)]$$

However, the outgoing decisions also encode the information regarding the ingress clock rate.

$$Y(z)_{input} = g[U(z)]$$

Applying superposition, $Y(z)$ is a function of $U(z)$ plus $E(z)$ (see Figure 11d).

$$Y(z) = Y(z)_{noise} + Y(z)_{input} = f[E(z)] + g[U(z)]$$

The transfer function $Y(z)_{input}/U(z)$ is a lowpass response (derived from Figure 11d). For a constant $U(z)$ value, which is the case for a stable fixed incoming ODUk/flex clock, $Y(z)_{input}$ would produce a constant or DC output. Therefore, the total $Y(z)$ output contains the error transferred to the output, $Y(z)_{noise}$, plus a DC value. If the output stream of the justification decisions is high-pass filtered to remove the DC component, the remaining signal represents the noise component. If the noise shaping implementation is compliant with the requirements of this standard, the spectrum of that noise component, normalized to unit amplitude justifications (+1,0,-1), should lie at or below the mask provided in Figure 12. To avoid removing too much low frequency content and since it has been determined that the noise shaping function essentially eliminates wander effects, the DC blocking low-pass function should not have a corner frequency above 10Hz (the wander limit).

The above approach can be applied in a number of ways. One might be to provide a real-time analog output representing the normalized justification decisions (+1,0,-1), measure the stream through an AC-coupled input of a spectrum analyzer (the AC-coupled high-pass response shall not have a corner frequency above 10Hz), and compare the result against the mask of Figure 12. A second might be to provide a digital stream of justification decisions and process the stream using FFT techniques. This could be performed real-time or performed off-line by storing the digital justification stream. In either case the DC component would be ignored and the result would be compared against the mask of Figure 12.

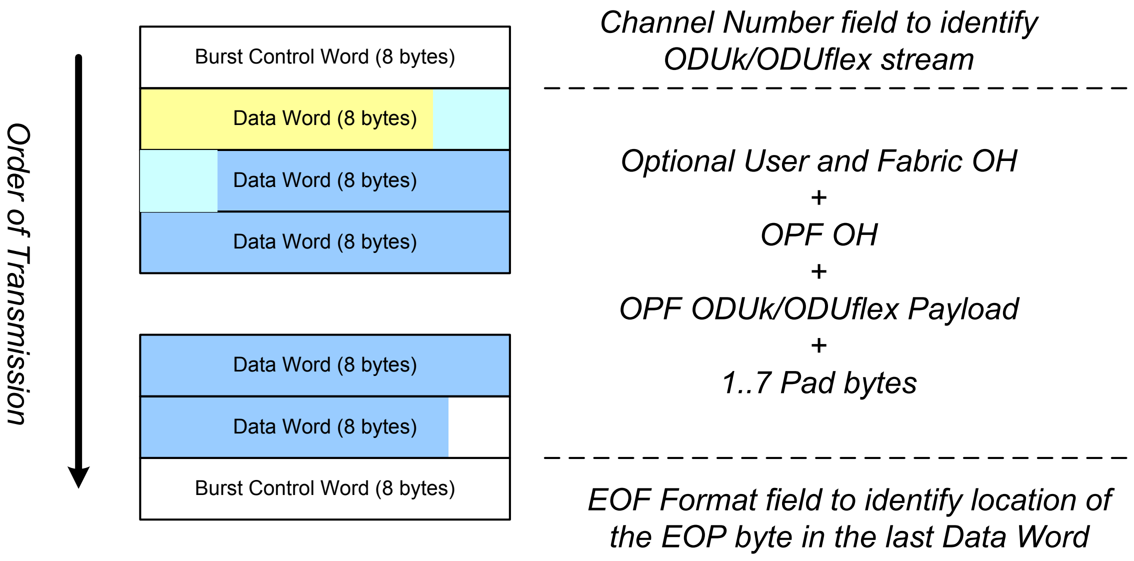
To support the validation mechanism described above it is recommended that each ingress packet size decision circuit implementation provide the ability to access the stream of justification decisions.

15 Appendix C: Mapping of OTN Over Packet Fabric Protocol Packets into Interlaken

This informative appendix describes the mapping of OTN Over Packet Fabric Protocol packets into Interlaken.

Interlaken is a packet oriented protocol. The basic unit is an 8-byte word. Payload data is carried in Data Words, while control information is carried in Control Words. An OFP packet can be transferred in one or more Interlaken bursts. Each burst consists of a leading Burst Control Word, a number of Data Words, and trailing Burst Control Word. The leading Burst Control Word contains a Channel Number field to identify the ODUk/ODUflex stream. The entire OFP packet, including the optional User the Fabric OH, the OFP OH and the ODUk/ODUflex payload bytes, is padded out to a multiple of 8 bytes. The Trailing Burst Control Word contains an EOP Format field that identifies the last byte of an OFP packet, so that the sink device can remove the pad bytes.

Figure 14 Interlaken Burst Format



16 Appendix D: Results of the PSD Governing Equations in Table 3

This informative appendix shows the recommended values of T, D_{nom}, D_{Δ}, and B_{nom} for various ODUk and ODUflex streams. In this example, the maximum payload size (B_{max}) is set to 120 bytes. Note that references to ODU rates above ODU4 are shown to illustrate scalability of the algorithms only, as the ITU has yet to define ODU5 and ODU6. Table 6 and Table 7 are taken from OIF2011.115.02.

Table 6 Parameters for Sample ODUk and ODUflex(CBR) streams

	ODU type	ODU bit rate Fodu (Gbps)	Scale Factor N	Dmax (bytes)	Bytes per ref clock tick	Tmax (ref clks)	Dnom in Tmax (bytes)	Tadj (ref clks)	T (ref clks)	Davg (bytes)	Dnom (bytes)	εnom (bytes)	εppm (bytes)	εact (bytes)	DΔ (bytes)	Bavg (bytes)	Bnom (bytes)
ODUk	ODU0	1.24416	1	120	0.5	240	120	2	238	119	119	0	0.0048	0.0048	1	119	119
	ODU1	2.498775	1	120	1.0042	119	119	0	119	119.5	119	0.5	0.0048	0.5048	1	119.5	119
	ODU2	10.037274	1	120	4.0338	29	117	0	29	116.9789	117	-0.021	0.0048	-0.0259	1	116.979	117
	ODU2e	10.399525	1	120	4.1793	28	117	0	28	117.0214	117	0.0214	0.0144	0.0358	1	117.021	117
	ODU3	40.319219	8	960	16.203	59	956	0	59	956	956	4E-07	0.0384	0.0384	2	119.5	119
	ODU3e1	41.774364	8	960	16.788	57	957	0	57	956.9263	957	-0.074	0.0384	-0.1121	2	119.616	119
	ODU3e2	41.785969	8	960	16.793	57	957	0	57	957.1921	957	0.1921	0.0384	0.2305	2	119.649	119
	ODU4	104.794446	16	1920	42.115	45	1895	0	45	1895.154	1895	0.1542	0.0768	0.231	2	118.447	118
	ODU5?	420	64	7680	168.79	45	7595	0	45	7595.486	7595	0.4861	0.3072	0.7933	2	118.679	119
	ODU6?	1051	128	15360	422.37	36	15205	0	36	15205.44	15205	0.4398	0.6144	1.0542	3	118.792	119
ODUflex(CBR	FC400	4.26785714	1	120	1.7152	69	118	0	69	118.3458	118	0.3458	0.0144	0.3602	1	118.346	118
	FC800	8.53571429	1	120	3.4303	34	117	0	34	116.6306	117	-0.369	0.0144	-0.3838	1	116.631	117
	IB SDR	2.5	1	120	1.0047	119	120	1	118	118.5539	119	-0.446	0.0144	-0.4605	1	118.554	119
	IB DDR	5	1	120	2.0094	59	119	0	59	118.5539	119	-0.446	0.0144	-0.4605	1	118.554	119
	IB QDR	10	1	120	4.0188	29	117	0	29	116.5445	117	-0.456	0.0144	-0.4699	1	116.544	117

Table 7 Parameters for Sample ODUflex(GFP) Streams

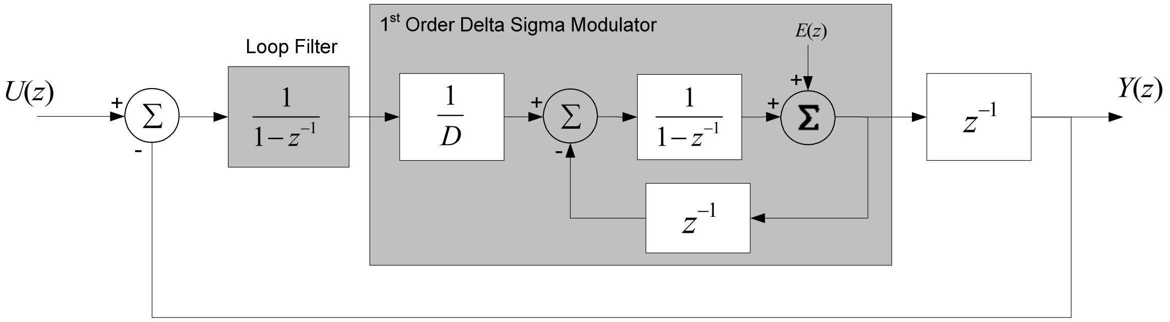
	ODU type	ODU bit rate Fodu (Gbps)	Scale Factor N	Dmax (bytes)	Bytes per ref clock tick	Tmax (ref clks)	Dnom in Tmax (bytes)	Tadj (ref clks)	T (ref clks)	Davg (bytes)	Dnom (bytes)	εnom (bytes)	εppm (bytes)	εact (bytes)	DΔ (bytes)	Bavg (bytes)	Bnom (bytes)
ODUflex(GFP)	n=1	1.24917723	1	120	0.502	239	120	2	237	118.9779	119	-0.022	0.0144	-0.0365	1	118.978	119
	n=2	2.49835446	1	120	1.004	119	119	0	119	119.4799	119	0.4799	0.0144	0.4943	1	119.48	119
	n=3	3.74753169	1	120	1.506	79	119	0	79	118.9779	119	-0.022	0.0144	-0.0365	1	118.978	119
	n=4	4.99670892	1	120	2.0081	59	118	0	59	118.4758	118	0.4758	0.0144	0.4902	1	118.476	118
	n=5	6.24588615	1	120	2.5101	47	118	0	47	117.9738	118	-0.026	0.0144	-0.0406	1	117.974	118
	n=6	7.49506338	1	120	3.0121	39	117	0	39	117.4718	117	0.4718	0.0144	0.4862	1	117.472	117
	n=7	8.74424061	1	120	3.5141	34	119	0	34	119.4799	119	0.4799	0.0144	0.4943	1	119.48	119
	n=8	9.99341784	1	120	4.0161	29	116	0	29	116.4678	116	0.4678	0.0144	0.4822	1	116.468	116
	n=9	11.2902332	8	960	4.5373	211	957	0	211	957.3685	957	0.3685	0.1152	0.4837	2	119.671	119
	n=10	12.5447035	8	960	5.0414	190	958	0	190	957.8727	958	-0.127	0.1152	-0.2425	2	119.734	119
	n=11	13.7991739	8	960	5.5456	173	959	1	172	953.8395	954	-0.16	0.1152	-0.2757	2	119.23	119
	n=12	15.0536442	8	960	6.0497	158	956	0	158	955.8561	956	-0.144	0.1152	-0.2591	2	119.482	119
	n=13	16.3081146	8	960	6.5539	146	957	0	146	956.8644	957	-0.136	0.1152	-0.2508	2	119.608	119
	n=14	17.562585	8	960	7.058	136	960	1	135	952.8312	953	-0.169	0.1152	-0.284	2	119.104	119
	n=15	18.8170553	8	960	7.5622	126	953	0	126	952.8312	953	-0.169	0.1152	-0.284	2	119.104	119
	n=16	20.0715257	8	960	8.0663	119	960	1	118	951.8229	952	-0.177	0.1152	-0.2923	2	118.978	119
	n=17	21.325996	8	960	8.5704	112	960	1	111	951.3188	951	0.3188	0.1152	0.434	2	118.915	119
	n=18	22.5804664	8	960	9.0746	105	953	0	105	952.8312	953	-0.169	0.1152	-0.284	2	119.104	119
	n=19	23.8349367	8	960	9.5787	100	958	0	100	957.8727	958	-0.127	0.1152	-0.2425	2	119.734	119
	n=20	25.0894071	8	960	10.083	95	958	0	95	957.8727	958	-0.127	0.1152	-0.2425	2	119.734	119
	n=21	26.3438774	8	960	10.587	90	953	0	90	952.8312	953	-0.169	0.1152	-0.284	2	119.104	119
	n=22	27.5983478	8	960	11.091	86	954	0	86	953.8395	954	-0.16	0.1152	-0.2757	2	119.23	119
	n=23	28.8528181	8	960	11.595	82	951	0	82	950.8146	951	-0.185	0.1152	-0.3006	2	118.852	119
	n=24	30.1072885	8	960	12.099	79	956	0	79	955.8561	956	-0.144	0.1152	-0.2591	2	119.482	119
	n=25	31.3617589	8	960	12.604	76	958	0	76	957.8727	958	-0.127	0.1152	-0.2425	2	119.734	119
	n=26	32.6162292	8	960	13.108	73	957	0	73	956.8644	957	-0.136	0.1152	-0.2508	2	119.608	119
	n=27	33.8706996	8	960	13.612	70	953	0	70	952.8312	953	-0.169	0.1152	-0.284	2	119.104	119
	n=28	35.1251699	8	960	14.116	68	960	1	67	945.7732	946	-0.227	0.1152	-0.342	2	118.222	118
	n=29	36.3796403	8	960	14.62	65	950	0	65	950.3105	950	0.3105	0.1152	0.4257	2	118.789	119
	n=30	37.6341106	8	960	15.124	63	953	0	63	952.8312	953	-0.169	0.1152	-0.284	2	119.104	119
	n=31	38.888581	8	960	15.628	61	953	0	61	953.3354	953	0.3354	0.1152	0.4506	2	119.167	119
	n=32	40.1430513	8	960	16.133	59	952	0	59	951.8229	952	-0.177	0.1152	-0.2923	2	118.978	119
	n=33	42.9484154	16	1920	17.26	111	1916	0	111	1915.861	1916	-0.139	0.2304	-0.3699	2	119.741	119
	n=34	44.2498825	16	1920	17.783	107	1903	0	107	1902.785	1903	-0.215	0.2304	-0.4456	2	118.924	119
	n=35	45.5513497	16	1920	18.306	104	1904	0	104	1903.831	1904	-0.169	0.2304	-0.3996	2	118.989	119
	n=36	46.8528168	16	1920	18.829	101	1902	0	101	1901.739	1902	-0.261	0.2304	-0.4917	2	118.859	119
	n=37	48.1542839	16	1920	19.352	99	1916	0	99	1915.861	1916	-0.139	0.2304	-0.3699	2	119.741	119
	n=38	49.4557511	16	1920	19.875	96	1908	0	96	1908.015	1908	0.0151	0.2304	0.2455	2	119.251	119
	n=39	50.7572182	16	1920	20.398	94	1917	0	94	1917.43	1917	0.4296	0.2304	0.66	2	119.839	119
	n=40	52.0586853	16	1920	20.921	91	1904	0	91	1903.831	1904	-0.169	0.2304	-0.3996	2	118.989	119
	n=41	53.3601525	16	1920	21.444	89	1909	0	89	1908.538	1909	-0.462	0.2304	-0.6923	2	119.284	119
	n=42	54.6616196	16	1920	21.967	87	1911	0	87	1911.153	1911	0.1533	0.2304	0.3837	2	119.447	119
	n=43	55.9630867	16	1920	22.49	85	1912	0	85	1911.676	1912	-0.324	0.2304	-0.5541	2	119.48	119
	n=44	57.2645539	16	1920	23.013	83	1910	0	83	1910.107	1910	0.1072	0.2304	0.3376	2	119.382	119
	n=45	58.566021	16	1920	23.536	81	1906	0	81	1906.446	1906	0.446	0.2304	0.6764	2	119.153	119
	n=46	59.8674881	16	1920	24.059	79	1901	0	79	1900.693	1901	-0.307	0.2304	-0.5377	2	118.793	119
	n=47	61.1689553	16	1920	24.582	78	1917	0	78	1917.43	1917	0.4296	0.2304	0.66	2	119.839	119
	n=48	62.4704224	16	1920	25.105	76	1908	0	76	1908.015	1908	0.0151	0.2304	0.2455	2	119.251	119
	n=49	63.7718895	16	1920	25.628	74	1897	0	74	1896.508	1897	-0.492	0.2304	-0.722	2	118.532	119
	n=50	65.0733567	16	1920	26.152	73	1909	0	73	1909.061	1909	0.0611	0.2304	0.2915	2	119.316	119
	n=51	66.3748238	16	1920	26.675	71	1894	0	71	1893.893	1894	-0.107	0.2304	-0.3371	2	118.368	118
	n=52	67.6762909	16	1920	27.198	70	1904	0	70	1903.831	1904	-0.169	0.2304	-0.3996	2	118.989	119
	n=53	68.977758	16	1920	27.721	69	1913	0	69	1912.722	1913	-0.278	0.2304	-0.508	2	119.545	119
	n=54	70.2792252	16	1920	28.244	67	1892	0	67	1892.324	1892	0.3242	0.2304	0.5546	2	118.27	118
	n=55	71.5806923	16	1920	28.767	66	1899	0	66	1898.601	1899	-0.399	0.2304	-0.6299	2	118.663	119
	n=56	72.8821594	16	1920	29.29	65	1904	0	65	1903.831	1904	-0.169	0.2304	-0.3996	2	118.989	119
	n=57	74.1836266	16	1920	29.813	64	1908	0	64	1908.015	1908	0.0151	0.2304	0.2455	2	119.251	119
	n=58	75.4850937	16	1920	30.336	63	1911	0	63	1911.153	1911	0.1533	0.2304	0.3837	2	119.447	119
	n=59	76.7865608	16	1920	30.859	62	1913	0	62	1913.245	1913	0.2454	0.2304	0.4758	2	119.578	119
	n=60	78.088028	16	1920	31.382	61	1914	0	61	1914.291	1914	0.2915	0.2304	0.5219	2	119.643	119
	n=61	79.3894951	16	1920	31.905	60	1914	0	60	1914.291	1914	0.2915	0.2304	0.5219	2	119.643	119
	n=62	80.6909622	16	1920	32.428	59	1913	0	59	1913.245	1913	0.2454	0.2304	0.4758	2	119.578	119
	n=63	81.9924294	16	1920	32.951	58	1911	0	58	1911.153	1911	0.1533	0.2304	0.3837	2	119.447	119
	n=64	83.2938965	16	1920	33.474	57	1908	0	57	1908.015	1908	0.0151	0.2304	0.2455	2	119.251	119
	n=65	84.5953636	16	1920	33.997	56	1904	0	56	1903.831	1904	-0.169	0.2304	-0.3996	2	118.989	119
	n=66	85.8968308	16	1920	34.52	55	1899	0	55	1898.601	1899	-0.399	0.2304	-0.6299	2	118.663	119
	n=67	87.1982979	16	1920	35.043	54	1892	0	54	1892.324	1892	0.3242	0.2304	0.5546	2	118.27	118
	n=68	88.499765	16	1920	35.566	53	1885	0	53	1885.002	1885	0.0017	0.2304	0.2321	2	117.813	118
	n=69	89.8012322	16	1920	36.089	53	1913	0	53	1912.722	1913	-0.278	0.2304	-0.508	2	119.545	119
	n=70	91.1026993	16	1920	36.612	52	1904	0	52	1903.831	1904	-0.169	0.2304	-0.3996	2	118.989	119
	n=71	92.4041664	16	1920	37.135	51	1894	0	51	1893.893	1894	-0.107	0.2304	-0.3371	2	118.368	118
	n=72	93.7056336	16	1920	37.658	50	1883	0	50	1882.91	1883	-0.09	0.2304	-0.3208	2	117.682	118
	n=73	95.0071007	16	1920	38.181	50	1909	0	50	1909.061	1909	0.0611	0.2304	0.2915	2	119.316	119
	n=74	96.3085678	16	1920	38.704	49	1897	0	49	1896.508	1897	-0.492	0.2304	-0.722	2	118.532	119
	n=75	97.610035	16	1920	39.227	48	1883	0	48	1882.91	1883	-0.09	0.2304	-0.3208	2	117.682	118
	n=76	98.9115021	16	1920	39.75	48	1908	0	48	1908.015	1908	0.0151	0.2304	0.2455	2	119.251	119
	n=77	100.212969	16	1920	40.273	47	1893	0	47	1892.847	1893	-0.153	0.2304	-0.3832	2	118.303	118
	n=78	101.514436	16	1920	40.796	47	1917	0	47	1917.43	1917	0.4296	0.2304	0.66	2	119.839	119
	n=79	102.815904	16	1920	41.319	46	1901	0	46	1900.693	1901	-0.307	0.2304	-0.5377	2	118.793	119
	n=80	104.117371	16	1920	41.842	45	1883	0	45	1882.91	1883	-0.09	0.2304	-0.3208	2	117.682	118

17 Appendix E: Examples of Converting Rate Decision (D) to a sequence of N packets of sizes $B_{nom} \pm 1$.

Two examples of PSD and PF implementations are given below for illustrative purposes. They are not intended to limit nor define compliant designs. In the first example, a packet size decision (D) is generated every T cycles of the 311.04MHz reference clock (REFCLK). The decision is segmented into N packet sizes using simple modulo arithmetic. Of the N packets, (D mod N) of those would have a size of B_{nom}+1 bytes and the rest would have a size of B_{nom} bytes. The sum of the N packet sizes is D. In this second example implementation, the PSD generates the size decision (D) of each packet directly, once every T/N cycles of the 311.04MHz system reference clock. Each decision sets the size of a single packet.

18 Appendix F: Noise Shaping Transfer Function Derivation

Figure 15 Noise Shaping Model



$$z^{-1}\left(E(z)+\left(\left(U(z)-Y(z)\right)\frac{1}{1-z^{-1}}\frac{1}{D}-Y(z)\right)\frac{1}{1-z^{-1}}\right)=Y(z)$$

Setting $U(z)=0$ and collecting terms yields

$$z^{-1}E(z)=Y(z)\left(1+\frac{z^{-1}}{1-z^{-1}}+\frac{1}{D}\frac{z^{-1}}{\left(1-z^{-1}\right)^{2}}\right)=Y(z)\left(\frac{D\left(1-z^{-1}\right)^{2}+Dz^{-1}\left(1-z^{-1}\right)+z^{-1}}{D\left(1-z^{-1}\right)^{2}}\right)$$

$$H_{NTF}(z)=\frac{Y(z)}{E(z)}=\frac{Dz^{-1}\left(1-z^{-1}\right)^{2}}{D-2Dz^{-1}+Dz^{-2}+Dz^{-1}-Dz^{-2}+z^{-1}}=\frac{Dz^{-1}\left(1-z^{-1}\right)^{2}}{D-\left(D-1\right)z^{-1}}$$

To find the noise transfer frequency response, set $z=e^{j\omega}$ and solve for the magnitude of $H_{NTF}(z)$. Note that the z^{-1} term in the numerator represents a pure delay term and has a magnitude of 1, therefore it can be omitted in the magnitude equation.

$$\left|H_{NTF}(z)\right| = \left|H_{NTF}(e^{j\omega})\right| = \left|\frac{D(1-e^{-j\omega})^2}{D-(D-1)e^{-j\omega}}\right| = \frac{D\left|1-\cos\omega + j\sin\omega\right|^2}{\left|D-(D-1)\cos\omega + j(D-1)\sin\omega\right|}$$

$$= \frac{D\left((1-\cos\omega)^2 + \sin^2\omega\right)}{\left|D-(D-1)\cos\omega + j(D-1)\sin\omega\right|} = \frac{2D(1-\cos\omega)}{\left|D-(D-1)\cos\omega + j(D-1)\sin\omega\right|}$$

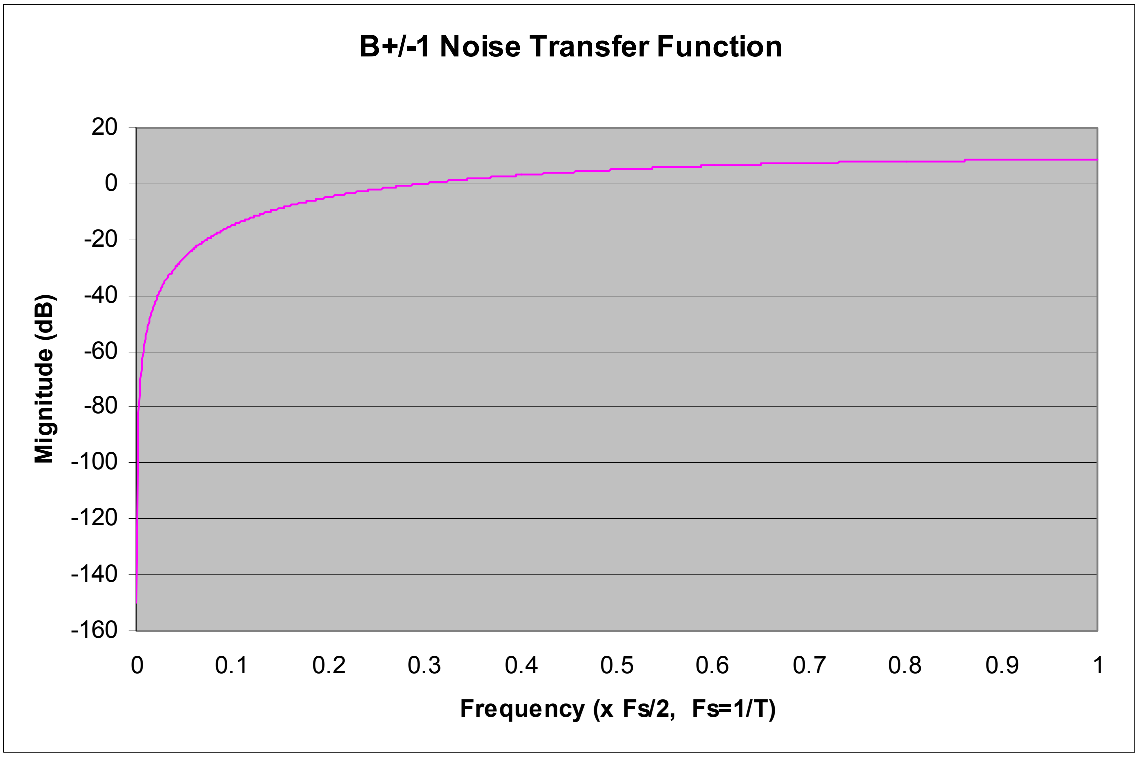
$$= \frac{2D(1-\cos\omega)}{\sqrt{(D-(D-1)\cos\omega)^2 + ((D-1)\sin\omega)^2}} = \frac{2D(1-\cos\omega)}{\sqrt{D^2 + (D-1)^2 - 2D(D-1)\cos\omega}}$$

Setting D=2, the noise transfer function is given as

$$\left|H_{NTF}(e^{j\omega})\right| = \frac{4(1-\cos\omega)}{\sqrt{5-4\cos\omega}}$$

A normalized plot of the noise transfer function is given below. The plot is for $0 \leq \omega \leq \pi$, where π represents half the sampling frequency, Fs/2, where Fs=1/T, the measurement period. The slope of the curve below the 3dB point is 40dB/decade.

Figure 16 B+/-1 Noise Transfer Function



19 Appendix G: List of companies belonging to OIF when document is approved

Acacia Communications
ADVA Optical Networking
Alcatel-Lucent
Altera
AMCC
Amphenol Corp.
Anritsu
AT&T
Avago Technologies Inc.
Broadcom
Brocade
Centellax, Inc.
China Telecom
Ciena Corporation
Cisco Systems
ClariPhy Communications
Cogo Optronics
Comcast
Cortina Systems
CyOptics
Department of Defense
Deutsche Telekom
ECI Telecom Ltd.
Emcore
Emulex
Ericsson
ETRI
EXFO
FCI USA LLC
Fiberhome Technologies Group
Finisar Corporation
Force 10 Networks
France Telecom Group/Orange
Fujitsu
Furukawa Electric Japan
Gennum Corporation
GigOptix Inc.
Hewlett Packard
Hitachi
Hittite Microwave Corp
Huawei Technologies
IBM Corporation
Infinera
Inphi
IP Infusion
JDSU
Juniper Networks
KDDI R&D Laboratories
Kotura, Inc.
LeCroy
Lightwire
LSI Corporation
Luxtera
Macom Technology Solutions
Marben Products
Maxim Integrated Products
Mayo Clinic
Metaswitch
Mitsubishi Electric Corporation
Molex
MoSys, Inc.
NEC
NeoPhotonics
Nokia Siemens Networks
NTT Corporation
Oclaro
Opnext
Picometrix
PMC Sierra
QLogic Corporation
Reflex Photonics
Semtech
SHF Communication Technologies
Sumitomo Electric Industries
Sumitomo Osaka Cement
TE Connectivity
Tektronix
Telcordia Technologies
Tellabs
TeraXion
Texas Instruments
Time Warner Cable
TriQuint Semiconductor
u2t Photonics AG
Verizon
Vitesse Semiconductor
Xilinx
Xtera Communications
Yamaichi Electronics Ltd.
ZTE Corporation

Notes