Flex Coherent DWDM Transmission Framework Document

OIF-FD-FLEXCOH-DWDM-01.0

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TITLE: **Flex Coherent DWDM Transmission Framework**

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ABSTRACT: This framework document specifies one technical approach to Flex Coherent DWDM Transmission in the application fields of long-haul, metro, and data center inter-connection, providing guidance to module and component suppliers on a technical direction of interest to a number of network equipment vendors.

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4 Document Revision History

Document	Date	Revisions/Comments
OIF-FD-FLEXCOH-DWDM-01.0	August 3rd, 2017	Release created from oif2016.483.02

Table 1: Document Revision History

5 Project Overview

5.1 Motivation

The OIF has begun its beyond-100G (B100G) efforts by investigating 400G implementation technology options in a recently completed white paper (OIF-Tech-Options-400G-01.0). As part of continued efforts, this project specifies one technical approach, namely Flex Coherent DWDM transmission, for diverse B100G network applications, including long-haul (LH), metro and data center inter-connection (DCI). This consensus on both the technical approach and the requirements for technology elements will provide clarity in the development required by system vendors and component suppliers.

5.2 Project Scope

This framework document targets functional architecture and building blocks for Flex Coherent transceiver implementation. In particular, the project will recommend flexible net bit rates, modulation formats, channel bandwidths, and optical carrier aggregation supported by a transceiver module. That module will serve as a basis to develop technical solutions for different network applications. The recommendation will be fully ITU-T G.694.1 flexible grid compliant, allowing the bandwidth to be optimized for the particular bit rate and modulation of an optical channel.

5.3 Excluded Items

This project excludes any other aspects and considerations on mechanical specifications, discrete optics or integrated optics, different fiber types and amplifier configurations, client interface modules, and other elements of DWDM transceiver line systems including optical MUX, DeMUX, amplifiers, and ROADMs.

6 Network Application Target and Objectives

This project addresses the following network applications and approximate distance targets with a common transceiver architecture:

- LH: 1000~1500 km
- Metro: 100~1000 km
- DCI: 50~100 km

Additionally, in view of the ever increasing industry needs and capacity demand resulting from double-digit traffic growth per year, and also the attempt from network operators to seamlessly upgrade these network segments with softwaredefined optics, the following network objectives have been agreed upon for this project:

- Being able to raise total capacity of systems by a factor of up to 4 with a maximum optical channel rate of 400 Gbps.
- Being able to maintain the maximum regeneration spacing of current LH networks in the range of 1000~1500 km
- Being able to support link adaptation by dynamically configuring modulation parameters according to the quality of channels and real data demand

, which provides for several transmission requirements as follows:

- Raising the total fiber capacity drives the choice of more spectrally efficient modulation formats than the DP-QPSK used for today's 100G, and also higher FEC coding gains to enhance the noise tolerance
- Maintaining the LH regeneration spacing sets the requirement of delivered optical signal to noise ratio (OSNR), and thus limits the achievable spectral efficiency (SE) per channel, making today's 50 GHz channel spacing insufficient for certain B100G LH applications. This motivates the following changes:
    - Increasing the channel spacing/bandwidth for a given channel rate
    - Aggregating two or more optical channels with achievable SEs as a single B100G superchannel
- Link adaptation support requires flexibility in modulation formats, bandwidths, and also channel rates

An additional requirement is that the channel rate upgrades be possible with currently deployed systems without requiring additional fibers or new optical amplifiers. Similar to the 100G ULH framework document, this Flex Coherent project will not seek to predict absolute propagation performance for its network application targets. It will leave that task to system vendors, and rely on them to provide feedback to the network operators.

7 Transceiver Architecture

7.1 Modulation and Coding

Modulation and coding flexibility plays an important role in Flex Coherent DWDM transmission. The design strategy of flexible modulation and coding is all about tradeoffs between SE and reach, where the latter is governed by OSNR. SE is measured in bits per second per Hertz (bits/s/Hz), which indicates the amount of bit rate transmitted over a band-limited channel. The amount of bit rate is the product of modulation efficiency (ME) in bits per symbol (bits/symbol) and symbol rate or Baud rate in symbols per second (symbols/s or Bd). Therefore, once both the reach and the bit rate are targeted, that strategy will come down to what channel bandwidths, symbol rates, and MEs are available, and how to manipulate these variables to meet those targets.

Subsection 7.1.1 starts by specifying channels for Flex Coherent DWDM transmission. This provides a foundation for studying available modulation techniques to reach the capacity target of this project. Subsection 7.1.2 describes the choices we have made in modulation system configuration and formats, and some of the rationale behind these choices.

As part of the Flex Coherent concept, forward error correction with variable coding gains and overheads are discussed in Subsection 7.1.3 that can be designed either independently or jointly with the modulation.

To ease management of Flex Coherent channels and promote multi-source module availability, Flex Coherent modulation capability is recommended in Subsection 7.1.4. Additionally, based on the specified Flex Coherent modulation functionality, available operational modes in terms of channel bandwidths, modulation formats, and the number of carriers for 400G sample applications are suggested in Subsection 7.1.5.

7.1.1 Channel

For ease of description, the following terms are adopted in this framework document:

- **Channel**: A frequency slot in a flexible grid supporting a single optical carrier
- **Channel Bandwidth**: The full width of a channel
- **Superchannel**: A frequency slot in a flexible grid supporting spectrally adjoining optical carriers sharing the same traffic load
- **Aggregate Channel Bandwidth**: The full width of a superchannel

Considering the transmission requirements, this project has adopted 37.5, 50, 62.5 and 75 GHz channels to develop Flex Coherent DWDM transmission solutions for its B100G network application targets. This allows signals with different bit rates and modulation formats to be assigned frequency slots with appropriated slot widths or channel bandwidths that would be required to optimize the individual channel.

In addition to choosing flexible grids, this project also specifies superchannel operation that can divide the data among two or more spectrally adjoining optical carriers, allowing each optical carrier to carry half or less the data rate that would be required for a single optical carrier. Better receiver sensitivity per optical carrier can be achieved at the expense of a wider overall spectral width. For practical reasons like component integration maturity, cost, and power dissipation, early implementation would limit the number of aggregated carriers to ***two***.

7.1.2 Modulation

This project leverages the fundamental modulation and detection scheme that has been adopted and specified in OIF 100G ULH framework document, i.e. dual polarization (DP) modulation with coherent detection. This provides baseline modulation efficiency (ME) and optical signal to noise ratio (OSNR) that would be available for an optical carrier before considering its modulation formats.

The distinct network application and bit rate targets of this project has driven the use of modulation formats with diverse MEs in addition to quadrature phase shift keying (QPSK) in the 100G project that has a ME of 2 bits per symbol. Therefore, this project has selected m-ary quadrature amplitude modulation (mQAM), where m is the modulation level, representing the amount of constellation points in power of two. QAM, a combination of both phase-shift keying (PSK) and amplitude-shift keying (ASK) designed to modulate the amplitude of in-phase and quadrature tributaries of a carrier in parallel, and then combine both as a whole, efficiently encoding $log_2(m)$ bits per symbol. Note that QPSK is functionally equivalent to mQAM with m equals to 4 although they are conceptually different. Here the ME is defined per polarization, which is doubled with dual polarization modulation.

This project has adopted modulation level m from 4 to 64, encoding 2 to 6 bits per symbol per polarization, respectively. The upper limit of the ME is primarily set by the effective number of bits (ENOB) of today's high sampling-rate analog to digital converters (ADC) and digital to analog converters (DAC), which is typically around 6 bits. In theory, encoding one more bit per symbol per polarization reduces receiver OSNR tolerance of a DP-mQAM signal by around 3 dB at a given symbol rate. Note that it is common practice to measure OSNR related parameters such as receiver OSNR tolerance and minimum OSNR on a per optical carrier basis, and this should also apply to superchannel scenarios.

7.1.3 Forward Error Correction

The actual transmitted signal bit rate is the sum of the payload data rate plus additional overhead for data encoding, transmission management and forward error correction (FEC). In addition to choosing multi-level QAM modulation formats, this project selected soft-decision forward error correction (SD-FEC) coding to improve the noise tolerance for higher-order modulations, favoring a ***multi-rate SD-FEC.*** The advantages of SD-FEC over hard-decision forward error correction (HD-FEC), and some implementation considerations have been detailed in a related OIF project, "100G Forward Error Correction White Paper (OIF-FEC-100G-01.0)."

As its name implies, a multi-rate SD-FEC shall have two or more overhead (OH) rates to choose from for different Flex Coherent design considerations in terms of network application and reach, modulation level, power dissipation, throughput, latency, etc. A practical OH rate of SD-FEC is typically below 30%, and the optimal OH rate may vary between network applications. The number of iterations of the SD-FEC might be tunable to trade-off the power dissipation and the required net coding gain (NCG) for the transmission link at a given OH.

In coherent optical transmission systems, modulation and coding are usually designed independently. For Flex Coherent transmission, however, a joint design of modulation and coding, so called coded modulation (CM), might be optionally employed to achieve higher coding gain than its counterpart at given OH and modulation format.

7.1.4 Recommended Modulation Functionality

To facilitate multi-source availability of Flex Coherent transceiver modules, this project recommends common modulation functionality per optical carrier between vendors in terms of net bit rates, modulation formats, and nominal channel bandwidths that would be required by network operators to upgrade their networks.

The recommendation of Flex Coherent modulation functionality is given in Table 2. It is recommended that Flex Coherent transceivers support 100 Gb/s, 200 Gb/s and 400 Gb/s net bit rates using DP-QPSK, DP-8QAM, DP-16QAM, DP-32QAM, and DP-64QAM modulation formats, which can be efficiently assigned nominal channel bandwidths of 37.5 GHz, 50 GHz, 62.5 GHz, and 75 GHz, respectively. Note that the modulation functionality is on an individual optical carrier basis, and any other add-on net bit rate and modulation format options are at the vendors' discretion.

It is realized that symbol rates for these net bit rate and modulation format combinations depend on different amounts of OH for FEC and other possible line coding. However, the symbol rates will be near 32 GBd, 43 GBd, 51 GBd, and 64 GBd for practical implementation, respectively, and are subject to about 15% range centered on these typical values depending on the amounts of coding OH selected. In addition, signal modulation bandwidths vary not only with the symbol rates, but also with different amount of excess bandwidths required due to the pulse shaping. The consideration of these facts suggests flexible channel bandwidth allocation for each symbol rate.

This project specifies nominal channel bandwidths of 37.5 GHz, 50 GHz, 62.5 GHz, and 75 GHz, which are ITU-T G.694.1 compliant with 12.5 GHz granularity, to efficiently accommodate those typical symbol rates, respectively. This allows assorted net SEs up to 8 bits/s/Hz, four times the net SE specified in the 100G framework document, which is in line with the primary project objective of up to four-fold increase in total system capacity. Moreover, this ensures Flex Coherent transceivers between vendors are consistent in the highest supported net SE.

These nominal channel bandwidths are reasonable approximations, but whether one can achieve the corresponding net SEs with acceptable penalties depends greatly on the passband characteristics of the optical filters (ROADMs, interleavers, MUX/DEMUX, etc.) in the channel, including the concatenated effect of all filters. That requires analysis for the particular channels assumed and for the particular modulation and coding scheme considered.

For network deployment with different design considerations, however, the channel bandwidth allocation is not limited to the values recommended in Table 2. For example, the 200 Gb/s DP-16QAM signal may be assigned the nominal channel bandwidth of 37.5 GHz, yielding a net SE of 5.33 bits/s/Hz. Alternatively, the same signal may be assigned a wider slot at a lower net SE to mitigate the passband narrowing impairments. Such flexible channel bandwidth

Nominal Channel Bandwidth (GHz)*		37.5	50	62.5	75
Net Bit Rate (Gb/s)	DP-QPSK	100		200	200
	DP-8QAM		200		
	DP-16QAM	200			400
	DP-32QAM			400	
	DP-64QAM		400		

* ITU-T G.694.1 compliant; however, finer granularities such as a half (6.25 GHz) or even a fourth (3.125 GHz) of the current slot width granularity may be required for higher and more flexible spectrum utilization.

Table 2: Recommended Flex Coherent Modulation Functionality per Optical Carrier

allocation is mainly at discretion of network operators or users, which might consider any slot widths where applicable.

It is technically feasible to allocate channel bandwidths at finer granularities for signals carrying the targeted net bit rates and modulation formats, achieving higher and more flexible spectrum utilization. Such granularities could be a half (6.25 GHz) or even a fourth (3.125 GHz) of the current slot width granularity.

7.1.5 Operational Modes and Sample Applications

The recommended Flex Coherent modulation functionality per optical carrier offers at least seven operational modes consisting of different modulation formats, (aggregate) channel bandwidths, and number of optical carriers for 400G sample applications, which are summarized in Table 3. For each application scenario, more than one preferred modes are recommended, which is based mostly on the theoretical analysis and experimental evaluation included in a related OIF project "technology options for 400G implementation (OIF-Tech-Options-400G-01.0)," and partially on the technology preferences of service providers listed in OIF's "400G White Paper Survey Results (oif2015.501.000)." All operational modes could be available for a dual-carrier transceivers, in which modes 1~4 are for two-carrier superchannel transmission with 200G per carrier, and modes 5~7 support two independent 400G channels. Only modes 5~7 are available for a single-carrier transceiver. Faster-than Nyquist or super-Nyquist technology using optimum receivers for signals with controlled inter-symbol interference (ISI) might be needed to enhance the LH system margin so as to maintain the targeted regeneration spacing in this project. Again, this project will not seek to predict absolute propagation distance for these operational modes. It will leave the task to system vendors, and rely on them to provide feedback to the network operators.

Operational Mode	Modulation Format	(Aggregate) Channel Bandwidth	Number of Carrier	Application Scenario		
				LH	Metro	DCI
1	DP-QPSK	150 GHz	2	•		
2	DP-QPSK	125 GHz	2	•	•	
3	DP-8QAM	100 GHz	2	•	•	
4	DP-16QAM	75 GHz	2		•	
5	DP-16QAM	75 GHz	1		•	•
6	DP-32QAM	62.5 GHz	1		•	•
7	DP-64QAM	50 GHz	1			•

Table 3: Available Operational Modes for 400G Sample Applications

7.2 Integrated Photonics

This project has leveraged the fundamental modulation and detection scheme of dual-polarization quadrature modulation with coherent detection from the 100G ULH project. Both projects have the same configurations of transmitter and receiver modules, but with different RF bandwidth and integration level requirements. With that, the OIF has approved two implementation agreements, "High Bandwidth Integrated Polarization Multiplexed Quadrature Modulators (OIF-HBPMQ-TX-01.0)," and "Micro Intradyne Coherent Receivers (OIF-DPC-MRX-02.0)," on polarization multiplexed quadrature (PMQ) modulator and micro intradyne coherent receiver (μICR), respectively, both targeting modulation and data-rate agnostic coherent applications with nominal symbol rates up to 64 GBd, and can fully support the recommended Flex Coherent modulation functionality for this project.

The support of superchannel operation with two or more aggregated optical carriers multiplies the amount of components that would be required for a single channel. This would suggest higher level of component integration for further cost and size reduction. Therefore, the OIF has started a project to develop a black-box specification for a fully integrated transmitter-receiver photonic module supporting up to two optical carriers.

7.3 Control and Management Interface

This project has adopted management data input/output (MDIO) as the primary control and management interface for Flex Coherent capable transceiver modules. A related OIF project will develop a centralized MDIO interface for all OIF-compliant coherent modules, in which a Flex Coherent clause would specify registers for implementing flexible DP-*m*QAM modulation, multi-rate FEC, scalable channel bandwidth/spacing, multi-carrier superchannel operation, and integrated photonics control functions.

7.4 Transceiver Building Blocks

Figure 1 shows how the major functional blocks of a Flex Coherent transceiver module discussed above come together. The macro block (in yellow) represents a Flex Coherent transceiver module supporting *n* network lanes, which comprises two micro functional blocks of flexible modulation and coding, and integration photonics for DP-*m*QAM and superchannel implementation, and all network lanes are interfaced to a central control and management unit. For the 400G sample applications discussed above, the corresponding network lanes amount *n* supported by a Flex Coherent transceiver module could be one or two.

For each network lane, the modulation and coding block consists of a FEC encoder/decoder, transmit (Tx) and receive (Rx) digital signal processors (DSP), and D/A and A/D converters, while the integration photonics block includes laser(s), and Tx and Rx optics modules, respectively, for DP-*m*QAM implementation. In addition, the modulation and coding block also include an adaptation function coordinating individual network lanes for multi-carrier superchannel implementation. The OTN framer that resides outside of the transceiver module is not the subject of this project.

Starting with the transmit direction, the incoming client signals are first framed according to OTN frame structure. After that they are fed into the adaptation block where (de)multiplexing and crossbar switching are performed

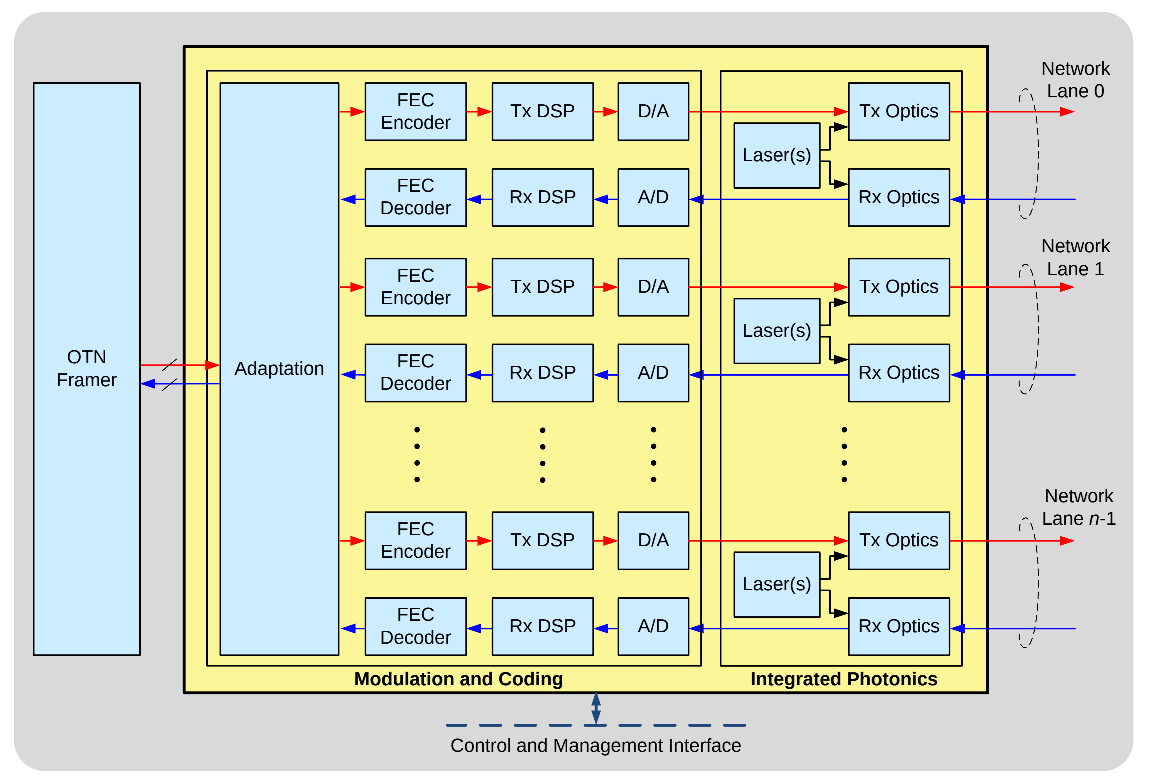

Figure 1: Blocks Diagram of a Flex Coherent Transceiver Module

as needed to match the payload rate required for each network lane, and to direct the signals to the designated network lanes for further Tx line-side signaling, respectively. More specifically, the adaptation function will split/inverse multiplex the OTUCn transport signal across OTUC slice boundaries across multiple carriers. On the receiver, after FEC decoding the OTUC slices are gathered from multiple carriers, deskewed and reordered to create the original OTUCn transport signal through the adaptation block. OTN framing is the final step. It should be noted that the OTN frame format to be supported by the Flex Coherent transceiver module could be the new OTUCn, the legacy OTU4, or both.

This framework identifies a Flex Coherent transceiver module functional architecture composed of a number of building blocks, but is not limited to specific electro-mechanical form factors for implementation. That choice depends on several interrelated aspects including the required power dissipation, the realizable level of photonic integration, the size of packaging, the desired partitioning of functions, and the acceptable implementation penalty. These detailed considerations will take place in related OIF projects.

8 Relationship to Standards Activities

This project is part of the efforts for B100G transport, and will require input standards under development by the IEEE and ITU-T to realize end-to-end system connection.

8.1 IEEE P802.3bs - 200 Gb/s and 400 Gb/s Ethernet Task Force

One of the objectives of the IEEE P802.3bs Task Force is to define 200 Gb/s and 400 Gb/s Ethernet to address the growing diverse bandwidth requirement, which are the desirable client signals to be supported in this OIF project.

8.2 ITU-T SG15 - B100G OTN

ITU-T SG15 has published the 5th edition of Recommendation ITU-T G. 709/Y.1331, "Interfaces for the Optical Transport Network," in which a new and flexible container, OTUCn, has been developed for B100G optical transport. The OTUCn frame structure is defined without a FEC area, and sub rates (OTUCn-M) are also specified, which are not constrained to be an integer multiple of 100 Gbit/s. This OIF project assumed the frame format for Flex Coherent transmission could be the new OTUCn and/or legacy OTU4.

9 <u>Summary</u>

This project identifies high-level system objectives and requirements for B100G network applications, and specifies one technical approach to Flex Coherent DWDM transmission, supporting flexible ranges at flexible channel rates. It identifies the functional architecture and building blocks of a Flex Coherent transceiver module with a special focus on the modulation flexibility, and also describes related OIF projects for specifying these technology building blocks. This would coordinate industry efforts toward a Flex Coherent transceiver ecosystem supporting the B100G network evolution.

This paper is the collaborative effort of many members of the OIF, including:

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