A Novel Flexible Optical-electrical Layer Coordinated OTN Interface with 1G Granularity Based on Probabilistic Shaping

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Abstract *A novel OTN interface capable of fine-granularity and cross-layer hitless adjustment, facilitated by probabilistic shaping with a small step of ~1G, is proposed for the first time, which could largely increase actual capacity utilization. Correspondingly a first real-time 1G granularity probabilistic shaping is experimentally demonstrated. ©2022 The Author(s)*

Introduction

Tremendous efforts have been invested on approaching the theoretical capacity limit of optical networks [1]. However, practical optical networks are running in a surprisingly inefficient fashion, and a large amount of capacity is being wasted due to some technical restrictions and operational reasons. Improving the efficiency of optical networks becomes of significant importance, with the benefits of cost reduction and power saving. Thus, an optical interface with features of large bandwidth, high efficiency and lossless rate adjustment is desirable.

As illustrated in Fig.1, there is quite a large gap between the optical channel capacity and the actual data rate of an Optical Transport Network (OTN) optical interface, including noise and interference which are difficult to eliminate, as well as link margin required and design waste which are actually reducible. In practice, two rarely noticed but important issues significantly impact the overall capacity utilization of optical communication systems. The first issue is that the optical layer and electrical layer of an optical interface, such as OTN interfaces, are individually configured and unable to perform small-step or hitless rate adjustment. The first issue somehow leads to the second issue that the optical interfaces are hardly able to adapt to the varying channel conditions and maximize the capacity utilization dynamically, automatically and imperceptibly. Therefore, it is necessary to study a novel approach with better efficiency and capabilities.

In this paper, to the best of our knowledge, for the first time we propose a novel OTN optical interface with two major attractive features. The first feature is that the optical layer and electrical layer of the interface are able to synchronously perform fine-granularity (~1G) and hitless rate adjustment, compared to the usual step of ~100G and the lossy rate adjustment currently. Secondly, based on the first feature, the actual capacity of the interface can more approach the maximal capacity of optical channels by adapting to the varying channel condition and

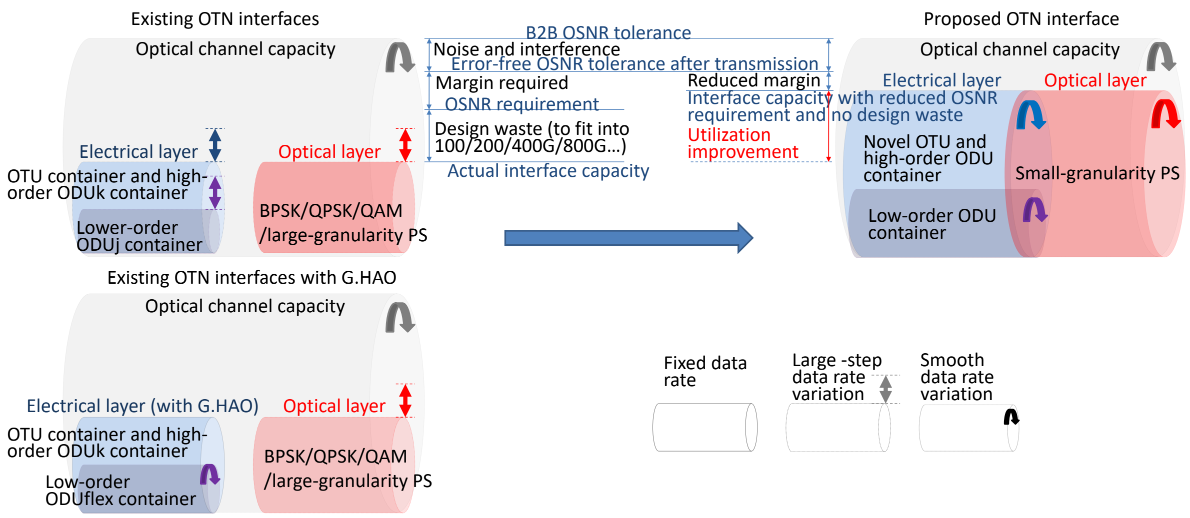

Fig. 1: existing OTN optical interface (left) and the proposed OTN interface (right)

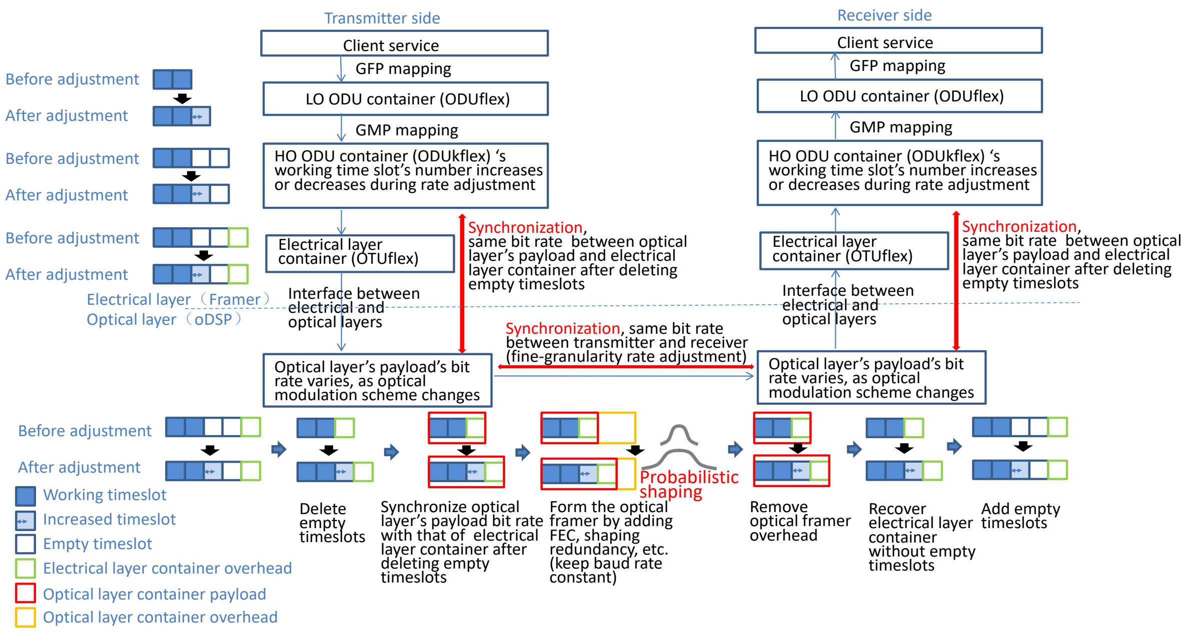

Fig. 2: Flowchart of the novel OTN interface.

customers' demand, in contrast to huge margin kept in current networks (after the deduction of noise and interference penalties, >3dB Optical Signal Noise Ratio (OSNR) margin is usually kept, which is approximately equivalent to a waste of >30% of the potential capacity). The rate adaptation could be even better with a Bit Error Rate (BER) probe and in an automatic manner. Finally, a first real-time 1G granularity probabilistic shaping (PS) is experimentally demonstrated base on FPGA implementation to verify its feasibility.

Scheme of the novel OTN interface

It is necessary to analyse the current techniques for a better understanding. The left-hand side of Fig. 1 illustrates existing OTN interfaces [2], typically consisting of an optical layer and an electrical layer. For example, the optical layer is set to a data rate, e.g. 100, 200, 400 Gb/s, with large step sizes, by using modulation formats of different orders. In parallel, the electrical layer is set to be a certain data rate container to match the rate of the optical layer accordingly, with large step sizes too, e.g. Optical Transport Unit 4 (OTU4) for 100Gb/s and OTUCn for n*100Gb/s. It should be noted that hitless data rate adjustment is possible for a few electrical containers, like Optical Data Unit k (ODUk) (k ≤ 4) carrying low-order container ODUflex inside, by running the G.HAO protocol [3]. However, the high-order container ODUk of the electrical layer by itself is a fixed rate container, so the combination of electrical and optical layers of an OTN interface is still unable to do small-step or cross-layer hitless bandwidth adjustment. Hence in practice, the rate adjustment of OTN interface is uncommon due to operational inconvenience caused by technical restrictions above.

To solve the problems above, a novel OTN interface is proposed on the right-hand side of Fig.1, which is able to achieve cross optical-and-electrical layer hitless bandwidth adjustment. In this OTN interface, the adjustment step of the optical layer is kept small so as to lower the requirement of buffer size during hitless adjustment. Meanwhile, the baud rate of the optical interface remains constant to simplify the hardware complexity and optimise the spectral utilization. Furthermore, the bit rate of optical layer's payload is synchronized with the bit rate of the electrical layer containers after deleting empty timeslots, both of which should be capable of small-step adjustment.

Specifically, PS technology could be adopted at the optical layer to keep the baud rate constant while still capable of changing the bit rate with a small step by varying the degree of shaping [4-8]. Different from most of previous research on PS, our design takes more advantage of small capacity variation, rather than transmission distance increase.

The flowchart of our proposed OTN interface is illustrated in Fig.2. At the transmitter side, client services are mapped into low-order containers, like ODUflex, and then low-order containers are mapped into the working time slots of high-order ODUk containers, named as ODUkflex here. After that, high-order ODUkflex containers are encapsulated by electrical layer containers, named as OTUflex, and pass through the interface between the electrical

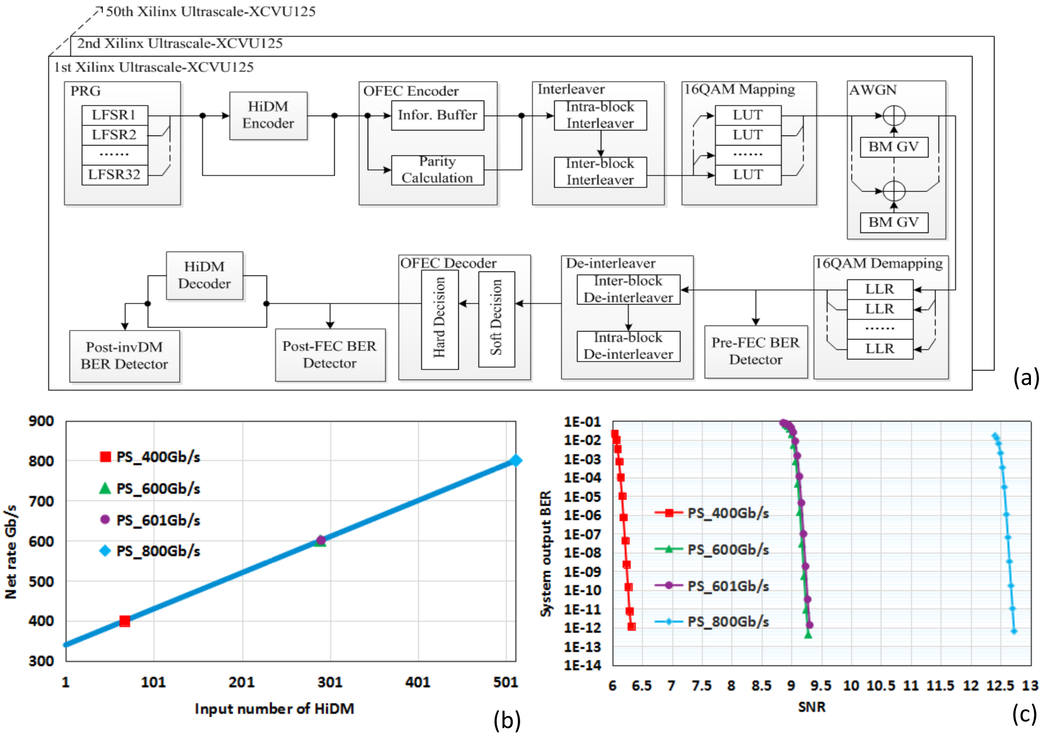

Fig. 3: (a) FPGA implementation of PS-16QAM (b) The net rate vs. Input number of HiDM (c) System output BER vs. SNR.

layer (e.g. framer chip) and optical layer (e.g. oDSP chip). At the optical layer, redundant empty timeslots of electrical layer containers are deleted, and subsequently electrical layer containers without empty timeslots are transported by optical frames with overhead of FEC, PS shaping redundancy, etc., through the optical link. At the receiver side, the procedure is reversed. During the rate adjustment with a varying number of working timeslots at the electrical layer, the bit rate of optical layer's payload always synchronizes with the bit rate of the electrical layer containers after deleting empty timeslots, facilitated by small-step PS to keep the baud rate constant while change the bit rate by varying the degree of shaping, over the optical link.

Experimental setup and results

As shown in Fig. 3(a), we implement a PS-16QAM system based on FPGA with Hierarchical Distribution Matching (HiDM) and Open Forward Error Correction (oFEC). On the transmitter side, the block size of HiDM encoder is 512, and the number of input bits can vary from 1 to 512. For PS-16QAM, the adjustment granularity of net rate is ~4*B*/512 where *B* is the system baud rate. The Box-Muller (BM) Gaussian Variate Generator (GVG) adds 32-lane uncorrelated Gaussian Variate with up to 32-bit accuracy which is used for simulating AWGN channel. The SNR is configurable with a tuning resolution of 0.005dB. On the receiver side, the system output BER is counted after HiDM decoder. We test 4 different shaping degrees where the number of input bits of HiDM are 68, 290, 291, 512, respectively. If we take 128G baud rate as an example, the net rate are ~400Gb/s, 600Gb/s, 601Gb/s and 800Gb/s, respectively. The relationship between net rate and input number of HiDM is shown in Fig. 3(b). The system output BER vs. SNR with different net rates is shown in Fig. 3(c), and we can see that when the net rate is adjusted with the smallest granularity of 1Gb/s, the required SNR changes less than 0.03dB, which means we can adjust the system net rate according to channel conditions finely and smoothly.

Conclusions

In conclusion, for the first time we propose a novel OTN interface with the capability of fine-granularity and cross-layer hitless rate adjustment, facilitated by PS technology with a small step of ~1G. This novel interface could largely increase the actual capacity utilization of optical networks by reducing the OSNR margin (usually >3dB). Finally, a first real-time 1G granularity PS is experimentally demonstrated. A similar rate adjustment mechanism could be applied to optical systems, such as Ethernet, passive optical networks, free-space, etc.

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