First Demonstration of Cognitive SDN Orchestration: A Real-time Congestion-aware Services Provisioning over OFDM-based 400G OPS and Flexi-WDM OCS Networks

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Abstract: Cognitive SDN orchestration over 400-Gbps OPS and Tbps-class Flexi-WDM networks is demonstrated, where the SDN-controllable OFDM transponders and the extended transport API enable the congestion-aware provisioning of end-to-end real-time services.

OCIS codes: (060.4250) Networks; (060.4259) Networks, packet-switched; (060.4080) Modulation

1. Introduction

Software-defined network (SDN) orchestration has been proposed and demonstrated as a feasible solution to efficiently manage end-to-end (E2E) services in multi- domain, technology, and tenant network (NW) scenarios [1]. Key enablers are: the Control Orchestration Protocol [2] (COP) for a transport API to allow interworking of heterogeneous control plane paradigms (e.g., OpenFlow, GMPLS/PCE); and the domain-specific sliceable bandwidth-variable transponders (S-BVTs) to provide adaptive-bandwidth E2E services [1, 3].

In this work, we experimentally demonstrate highly flexible and intelligent inter-domain coordinated actions based on the SDN orchestration, namely *cognitive SDN orchestration*. It is a promising solution to realize the cognition cycle [4] across the heterogeneous NW domains (Fig. 1a). In order to demonstrate the concept, an advanced multi-domain/technology testbed is implemented, which consists of a 400-Gbps variable-capacity optical packet switching (OPS) domain and a >1-Tbps Flexi-WDM optical circuit switching (OCS) domain controlled by individual SDN controllers. In the data plane, different OFDM-based S-BVTs are employed for inter/intra-domain links for adaptive and fine-granular E2E service provisioning. For cognition, SDN-capable domain-specific optical performance monitors, such as a 10-MHz-resolution optical channel monitor, are also introduced. In the control plane, the ABNO architecture [1] has been extended and addressed as a cognitive SDN orchestrator. As a use case, we demonstrate a real-time congestion-aware provisioning of E2E services including an inter-domain HD video streaming. The orchestrator detects traffic congestion of specific flows, allowing congestion control via e.g. OFDM rate-adaptation for packet compression in the OPS domain, and improves the QoS of the E2E services in a self-healing manner.

2. Testbed Implementation

The data plane of our testbed was implemented at NICT premises in Sendai, Japan. The data plane includes two NW domains: a 400G-class discrete multi-tone (DMT)-based OPS NW and a Tbps-class Flexi-WDM OCS NW. Each

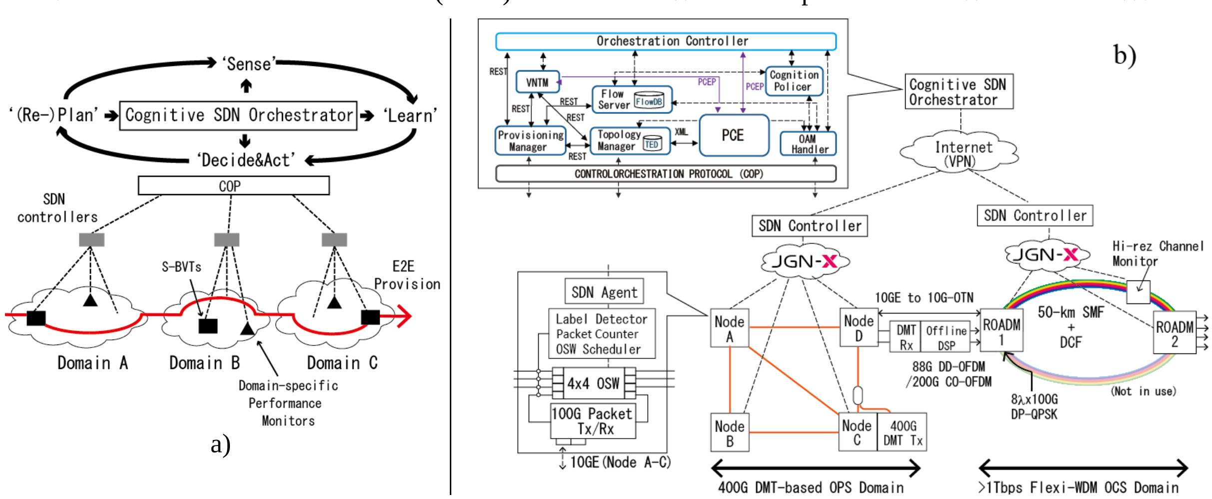


Fig.1 (a) Cognitive SDN orchestration concept and (b) its testbed implementation.

domain was controlled by an individual custom SDN controller at KDDI premises in Saitama, Japan, through JGN-X [5]. Both domains were orchestrated by a cognitive SDN Orchestrator deployed at CTTC premises in Barcelona, Spain, through a VPN connection.

In the data plane, the OPS domain consisted of 4 OPS nodes (A-D) shown in Fig. 1b. A 400G ($100G \times 4\lambda$) DMT and a 100G-OOK ($10G \times 10\lambda$) were employed as optical payload formats. The nodes A-C based on 4×4 SOA switches (SWs) [6], and node D employs a 4×4 PLZT SW for the transparent switching of the DMT packets. The 100G packet transponders at node A-B are real-time and have 10GE client signal interface. A semi-real-time DMT packet transmitter was implemented at node C and the receiver was at the output of node D output. Most of the NW entities in the domain were SDN-controllable. Particularly, the DMT transponder has the capability to adapt the payload format based on *policy* (e.g., full-rate, half-rate, energy-saving etc.) given by the SDN controller. As a performance monitor for cognition, the optical packet counters (OPC) were implemented at each node, which reports how the link is congested to the SDN controller. Meanwhile, the OCS domain was a 50-km diameter ring NW with 2 flexi-grid ROADMs (1-2), which based on 1×4 programmable WSSs. At ROADM1, a 200G (48Gbaud, 32QAM) single-pol. CO-OFDM, an 80G DD-OFDM, and a 10G-OTN (i.e. OTU2e) transponders were deployed as the OPS-to-OCS interface. Both OFDM transponders were implemented with offline DSP. The 10G-OTN was carrying real-time data. All three transponders were used as single S-BVT whose bandwidth was decided via the SDN controller depending on the reach/purpose of the established connections; e.g., using DD-OFDM for metro-access distances. In addition, $8\lambda \times 100G$ DP-QPSK channels were implemented to demonstrate >1-Tbps Flexi-WDM NW operation. A non-intrusive performance monitoring system was deployed for cognition, composed of a 10-MHz-resolution optical spectrum analyzer, a notifications server and a monitoring agent. This system was extracting WDM channel allocation, effective guard-band, signal power and OSNR of each multi-format Flexi-WDM channel.

The SDN orchestrator was based on the ABNO architecture (Fig. 1b) [5] using a COP based on YANG/RESTCONF [4]. To enable the cognition cycle, its ABNO architecture has been extended by newly adding a Cognition Policer module, which provides updates on the optimization criteria to the orchestrator controller based on the NW status information received from the control plane through the OAM Handler (Fig. 1b).

3. Use Case and Results: Congestion-aware Real-time Inter-domain Service Provisioning

A real-time congestion-aware provisioning of E2E services was demonstrated in the multi-domain testbed. In the demo, two inter-domain flows were generated sequentially. The first one was for the real-time HD video streaming. A full-HD camera with IP-based media gateway was located at node A in the OPS domain, and another gateway and a HD display system were at ROADM2. The video traffic was based on 10GE and converted to a 10G-OTN signal at node D in real-time. The second flow originated from the DMT transmitter at node C. The flow was *logically* interfaced by the DD-OFDM transmitter also at node D and then transferred to ROADM2. The effective bit rate of the flow was around 15 Gbps (packet rate was 17% at 100G).

In the OPS domain, first, the controller learnt some thresholds for the OPC value to sustain the intra-domain packet loss ratio (PLR) < 1% in an offline manner. After generating the first and second flows, OPC at node D detected the congestion (1-2 in Fig. 2a). To avoid the contention of optical packets, the controller decided to change the transmission policy for the DMT flow (3 in Fig. 2a). Then, the DMT transmitter compressed the optical packets in the

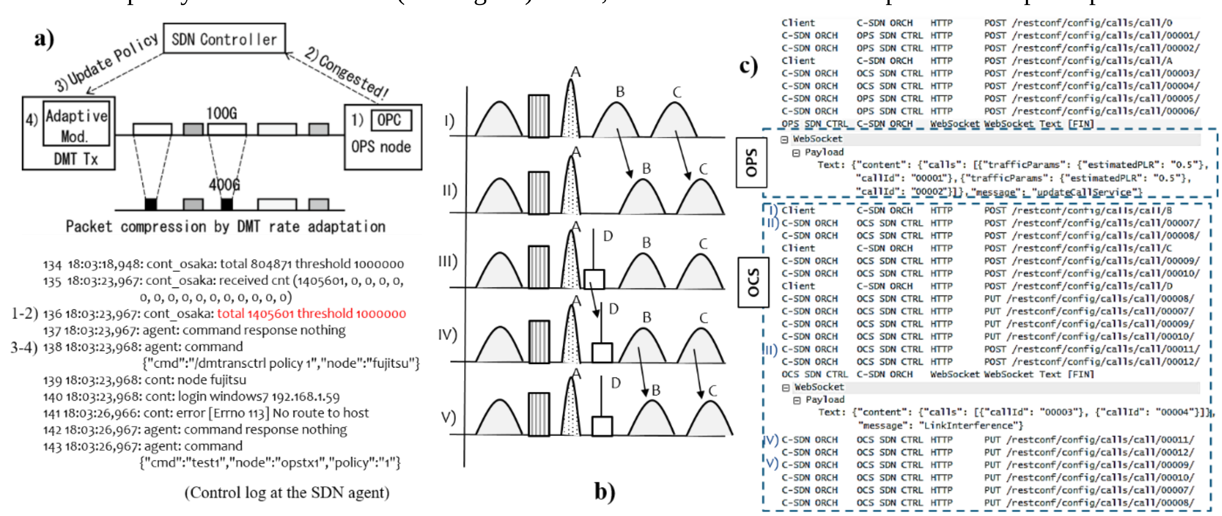
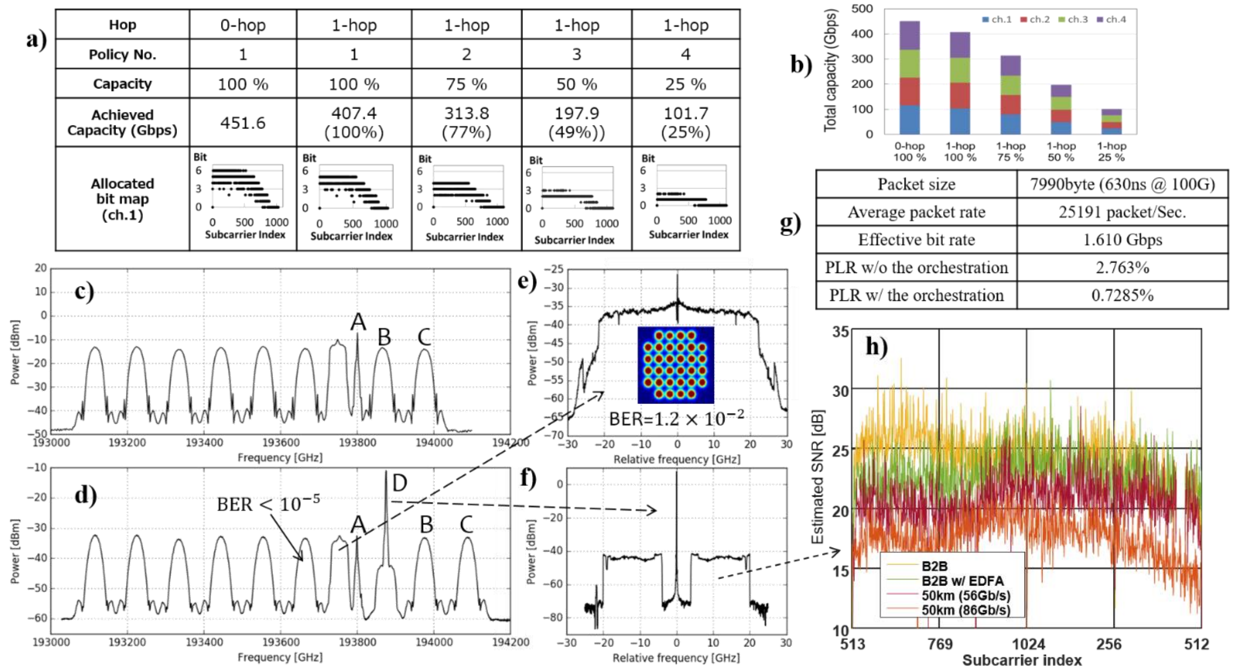


Fig. 2 Cognitive SDN orchestration use cases: a) SDN-enabled OPS congestion control via DMT rate-adaptation; b) OCS congestion control via spectrum re-allocation and guard-band adjustment; c) control traffic capture.



Hop	0-hop	1-hop	1-hop	1-hop	1-hop
Policy No.	1	1	2	3	4
Capacity	100 %	100 %	75 %	50 %	25 %
Achieved Capacity (Gbps)	451.6	407.4 (100%)	313.8 (77%)	197.9 (49%))	101.7 (25%)
Allocated bit map (ch.1)					

Packet size	7990byte (630ns @ 100G)
Average packet rate	25191 packet/Sec.
Effective bit rate	1.610 Gbps
PLR w/o the orchestration	2.763%
PLR w/ the orchestration	0.7285%

Fig. 3 Experimental results: a-b) Achieved bitrate of DMT packets; c-d) WDM spectra before/after re-allocation and cognition; e-f) CO/DD-OFDM signal spectra; h) per-subcarrier SNR for DD-OFDM signal; g) PLR of E2E HD video streaming channel.

time domain to reduce the link occupancy by the adaptive modulation (4 in Fig. 2a). Figure 3a and b show the characteristics of the semi-realtime DMT transponder with different transmission policies. The total achievable capacity was up-to 407.4Gbps (100G× 4λ) after 1-hop. As shown in figures2a-b, the capacity properly adapts as the policy changes. In the provisioning, the policy was changed automatically from 4 to 1 and the DMT packets were compressed 1/4 in the time domain to reduce PLR of the two flows while preserving the capacity of the DMT flow.

In the OCS domain, the cognition was needed particularly to set up the DD-OFDM channel (carrying the second flow). The occupancy of the OCS domain after setting the 10G-OTN channel (the first flow) is shown in Fig. 2b, step I (corresponding to Fig. 3c). There it can be observed that the E2E 10G-OTN signal (A) was surrounded by the CO-OFDM and PM-QPSK signals (B, C). Since OFDM signals had sharp spectral edges (see Fig.3e-f), CO-OFDM and 10G-OTN were narrowly spaced. Given this initial status, a new request D asked a DD-OFDM flow to be routed through the monitored link (Fig. 2c, step I). Signal D is implemented with a DFB laser, with limited tunability, leading to strict allocation requirement. Thus, the SDN controller in the OCS domain re-allocated B and C signals (Fig. 2b-c, step II), which were occupying the spectrum slot requested for D. Next, D was allocated, 50 GHz-spaced with respect to A, and the performance monitor raised a notification of estimated performance degradation of A (Fig. 2b-c, step III). In fact, the peak power difference between A and D was 21.6 dB, leading to a possible nonlinear interaction for the spacing initially set. Thus, the SDN orchestrator modified the frequency spacing to 75 GHz; integrating the new value learnt into the cognitive orchestration (Fig. 2b-c, step IV). Finally, B and C signals, adjacent to D, were re-allocated according to the spacing learnt. This is shown in Fig. 2b-c, step V, corresponding to the spectrum of Fig 3d.

Eventually, the DD-OFDM channel achieved a total bitrate of 85.6 Gbps with a BER of 1.3×10^{-3} (error-free after applying FEC). Consequently, the FEC error-free operation with the required bandwidth in the both domains was confirmed for the flow from node C to ROADM2 (DMT packet to DD-OFDM). Meanwhile, Fig. 3 g) represents the PLRs observed at the IP-based media gate way at ROADM2 for the real-time HD video streaming. The initial PLR was 2.76%, but was automatically reduced to 0.728% under the cognitive SDN orchestration.

4. Conclusions

Cognitive SDN orchestration of multi-technology multi-domain optical networks was proposed and demonstrated experimentally for the first time.

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