Control of Packet over Multi-Granular Optical Networks combining Wavelength, Waveband and Spatial Switching For 6G transport

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Abstract: This paper presents an end-to-end transport SDN control system for packet (IP) and multi-granular (WDM/WBDM/SDM) optical networks for 6G transport. The dynamic routing and resource assignment combining wavelength, waveband, and spatial resources is also addressed.

1. Introduction to packet over multi-granular (WDM/WBDM/SDM) optical networks for 6G transport

The sixth generation (6G) of mobile networks is expected to revolutionize the way we communicate and sense with promises of faster speeds, greater bandwidth, lower latency, and higher reliability. From a control and management perspective, it is essential to provide customers with end-to-end (E2E) 6G network services complying with negotiated Service Level Agreements (SLAs). This requires covering all different technological domains, such as the Radio Access Network (RAN), Core Network (CN) but also Transport Network (TN) (Fig.1a). The 6G mobile operator could assign the resources depending on the requirements to meet, including radio, computing and transport network resources. Transport network services can be deployed between RAN network functions (i.e., fronthaul and midhaul), between CN network functions located at the edge and core computing infrastructure, or between RAN and CN network functions (i.e., backhaul). To this end, it is required to deploy an E2E transport software defined networking (SDN) control system that interfaces with the overall 6G management system.

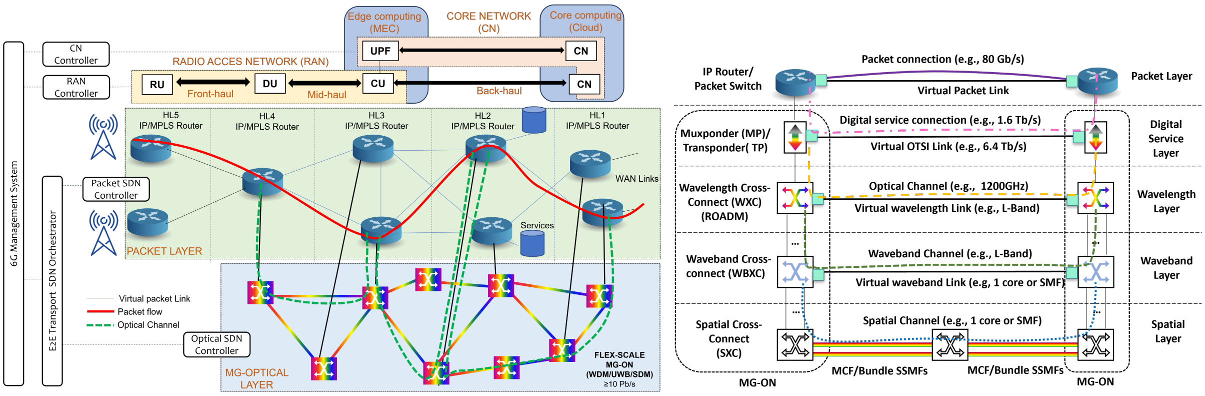
Mobile transport network design heavily relies on multi-layer technology featuring packet nodes (i.e., IP/MPLS routers) on top of optical nodes (i.e., ROADMs). The packet layer is arranged in a five-level hierarchical aggregation/distribution structure where most traffic goes from edge nodes to metro-core nodes [1]; Hierarchy level (HL)1 and HL2 are the top gateways of most MAN traffic; HL3 is the transit level that aggregates the traffic from HL4 nodes; HL4 are large central offices that aggregate traffic from HL5 access nodes (such as mobile base stations). Packet nodes interface with the optical networks through optical transponders with grey pluggable client optics (Fig.1b). Essentially, an IP router of hierarchical level n is logically connected (using an optical channel traversing multiple ROADMs in the optical layer) to one or two routers at the next hierarchical level n+1.

6G radio parameters have not been defined yet but extrapolating the reference values considered in 4G and 5G, we can consider that peak capacity requirements of the 6G transport connections will range from hundreds of Gb/s to $\geq$ 1 Tb/s [2]. To scale the capacity of the optical links to meet these requirements,it will be required to combine heterogeneous multiplexing division approaches such as wavelength (WDM), waveband (WBDM) and spatial (SDM). It will enable to scale optical link capacities $\geq$ 1 Pb/s, as developed in the EC FLEX-SCALE project. The resource control of multi-granular optical nodes (MG-ON), combining wavelength, waveband, and spatial switching is very challenging.

2. End-to-end transport SDN control system for packet over multi-granular optical networks

A typical transport SDN control system can comprise a packet layer SDN controller and an optical layer SDN controller, which are managed and coordinated by a E2E transport SDN orchestrator. The E2E transport SDN orchestrator is responsible for managing the overall network policies and routing rules for both the packet and optical layers, ensuring that the transport network operates optimally and efficiently from end-to-end, while meeting the requirements of the 6G transport services. The implementation of an E2E transport SDN orchestrator could rely on a cloud-native architecture such as TeraFlowSDN (TFS) [3], where diverse micro-services host individual functions (within containers) interacting via well-defined APIs and workflows.

In this approach, if a new virtual packet link with a given capacity (for example 1.6 Tb/s) between a pair of packet nodes is required, the packet SDN controller can issue a request to the E2E transport SDN orchestrator to ask for an additional virtual packet link. Upon the reception of this request, the transport SDN orchestrator can request to the optical SDN controller the provisioning of a digital service connection with the same capacity (i.e., 1.6 Tb/s), between the pair of optical transponders (TP)/ muxponders (MP) connected to the source and destination packet nodes. Then, the optical SDN controller provisions an optical channel (also known as media



(a) (b)

Fig. 1: Packet over Multi-granular Optical networks for 6G transport. a) End-to-End 6G management for RAN, core network and MG-ON transport network. b) MG-ON architecture with WDM/WBDM/SDM

channel) between the pair of optical TP/MP with the required spectrum for the maximum capacity. For example, if the pair of TP/MP supports 6.4 Tb/s, the spectrum needed for the optical channel would be 1200 GHz. To this end, the optical SDN controller applies a Routing, Fiber, Band, and Spectrum Assignment (RFBSA) algorithm to compute and assign the needed optical resources in the multi-granular optical network, as described in Sec.3. After the provisioning of the optical channel, the optical SDN controller setups a virtual optical tributary signal (OTSi) link between the pair of TP/MP with a bandwidth equal to the maximum capacity of the TP/MP (e.g., 6.4Tb/s), and reserves the bandwidth requested by the E2E transport SDN orchestrator (i.e., 1.6Tb/s). In this way, the optical SDN controller could allocate future digital service connection requests between the same pair of MPs without setting up new optical channels, provided that there is enough available bandwidth in the virtual OTSI link. Once the provisioning of the digital service connection is completed, the E2E transport SDN orchestrator notifies the packet SDN controller that the requested virtual packet link is active. Then, the packet SDN controller can update its internal topology and provision flows using this new virtual packet link.

3. Dynamic routing and resource assignment in multi-granular (WDM/WBDM/SDM) optical networks

In Multi-granular (WDM/WBDM/SDM) Optical Networks, the dynamic routing and resource assignment may experience delays due to the increased switching complexity inherent in the MG-ON architecture. The MG-ON are composed of Spatial Cross-Connects (SXC)- used for fiber switching; Waveband Cross-Connects (WBXC)- used for waveband switching; and Wavelength Cross-Connects (WXC)- used for spectrum switching. In this paper, we purpose multiple virtual layers on the top of the SDM layer to reduce switching complexities. With the introduction of the virtual layer, the complexity of the routing and resource assignment can be reduced significantly [4].

Routing and Spectrum Assignment is one of the essential components in Flexible-grid Optical Networks. In this paper, we are using SDM and WBDM, in addition to WDM systems; therefore, the problem extends to Routing, Fiber, Band, and Spectrum Assignment (RFBSA). The objective of dynamic RFBSA is to seek an optimal path with sufficient available resources between source-destination nodes fulfilling the service requirements. Some constraints need to be satisfied while executing the RFBSA. In this regard, herein, it is prioritized selecting the path through the same fiber out of a bundle of fibers. Also, the same waveband must be used throughout the route, and the set of spectrum slots must be same throughout the link (contiguity) and route (continuity).

An undirected network graph G consists of a V set of nodes $v \in V$, E set of Edges $e \in E$. There are multiple fibers F between each pair of nodes *(i,j)* where $(i,j) \in E$, $i \in V$, $j \in V$. Each fiber further has multiple wavebands (S+C+L). The wavebands are further divided into 12.5 GHz multiple spectrum slots. A Lightpath Request $LR(s,d,SS^r)$ is defined by the tuples source node s, destination node d and required continuous spectrum slots SS^r. Different layers have different node and edge relationships based on the arrival and release of the LRs. Therefore, the terminology changes for each layer, defined as follows. $G^s(V^s,E^s)$ for spatial layer. Here, each edge E^s consists of the Bundle of fibers. Next, the graph for the virtual waveband layer $G^b(V^b,E^b)$ where each edge E^b have S+C+L wavebands. Whereas, the graph for the virtual wavelength layer is $G^w(V^w,E^w)$, each edge E^w have multiple spectrum slots. Initially, E^b and E^w are empty.

Figure 2 describes the sequence of steps opted for RFBSA. An LR arrives, and the routing process initiates from the Wavelength layer. If a route with the required continuous and contiguous SS^r from s to d on G^w is found, an Optical Channel (OCh) will be set. If not found, the route will be checked on the following lower-level graph $G^b(V^b,E^b)$ for the waveband layer. A Waveband Channel (WBCh) will be set up on $G^b(V^b,E^b)$ if a route is available with the same waveband from s to d, and a new edge between s to d will be added as a virtual wavelength link on G^w. Then, the route with SS^r will checked on G^w and the OCh will be set. Even if there is no route from s

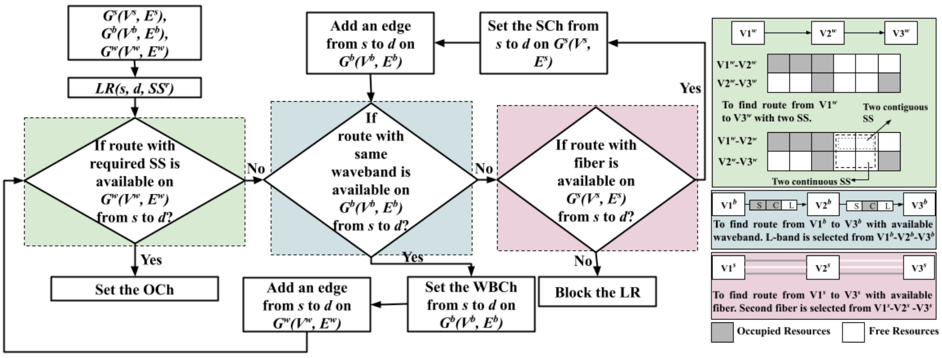
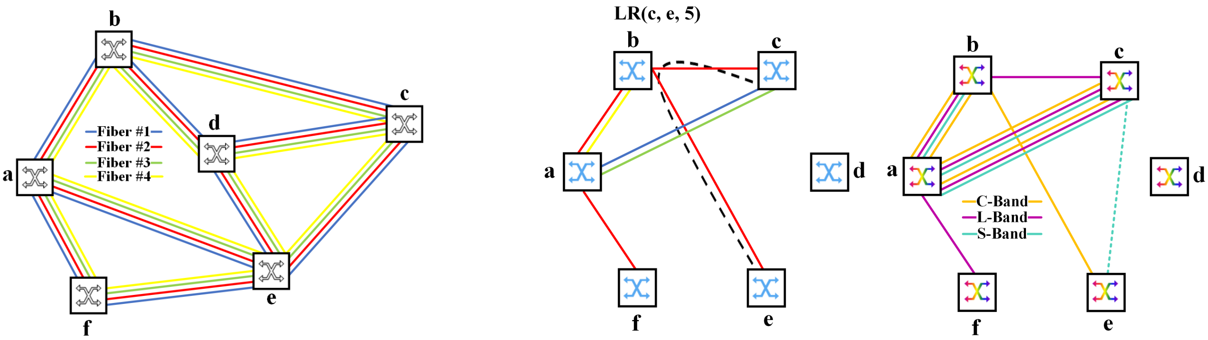


Fig. 2: RFBSA Flowchart. Example of Routing and Resource Assignment at each layer independently.

to d on G^b, the route will be checked on the Spatial layer G^s. If there is a route from s to d with an available fiber on all edges, then a Spatial Channel (SCh) is set from s to d on G^s. Next, a new edge between s to d will be added on G^b as a virtual waveband link. Then, after setting WBCh on G^b, another new edge is added on G^w as a virtual wavelength link from s to d. Then, the route with SS^r will checked on G^w and the OCh will be set. Otherwise, the LR will get blocked if no route with available fibers is on G^s. Whenever an LR is released, if there are other OChs on e^w or WBChs on e^b from released s to d, then leave the edge on the graph intact. However, if there is no OCh on that edge or edges, then delete that edge/s from G^w. Also, if all the wavebands are free, then delete the responsible edge/s from G^b.



(a) (b)

Fig. 3: An example of RFBSA. (a) An example network $G^s(6,9)$, each edge $e^s \in E^s$ is a bundle of four fibers, (b) The structure of $G^b(6,8)$ and $G^w(6,16)$ after a few LRs.

Fig. 3 shows an example of RFBSA with the arrival of each LR. An example network $G^s(6,9)$, with six nodes and nine edges is shown in Fig. 3a. Dynamic arrival and departure of the LRs changes the structure of G^b and G^w as shown in Fig. 3b. For example, earlier, there was no link from c to e in G^w. When *LR(c,e,5)* arrives, the route with continuous spectrum will be first searched on G^w as it is not available; therefore, the route with continuous waveband will be searched on G^b from *c-b-e* and a new virtual wavelength link (dashed S-band) is set on G^w. Now, the LR can be set from c to e with a requirement of five spectrum slots.

4. Conclusions

The control of Packet over multi-granular (WDM/WBDM/SDM) optical networks will be required for mobile transport networks in order to meet the capacity requirements and network services foreseen for 6G.

Acknowledgments

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