SDN/NFV Control and Orchestration of Dynamic Optical Beamforming Services for Beyond 5G Fronthaul Networks

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Abstract *This paper presents and experimentally validates an SDN/NFV architecture for the management of optical beamforming connectivity and network services for beyond 5G fronthaul, controlling OBFN coherent and incoherent systems, ARoF transceivers, BBUs with analog output/input and RRHs.*

Introduction

Beamforming has been identified as a key technology for 5G to overcome the increased path loss at mm-wave and to increase the possible rate of frequency reuse by focusing the emitted energy in a confined area. It enables to deploy radio remote heads (RRHs) with multiple beams that can be dynamically steered. However, electrical beamformers face challenges with regards to energy consumption, footprint and heat dissipation, causing multi-beam transmission with continuous steering of the beams to be a highly difficult task[1]. Optical beamforming (OBF), on the other hand, allows the compact integration of entire optical beamforming networks (OBFNs), due to the large wavelength difference between optical and RF signals[1]. The deployment of OBF for beyond 5G fronthaul requires the combination of analogue radio-over-fiber (ARoF) transceivers connected to base-band units (BBUs) with analog output/input in the central office (CO) and the remote unit (RU), and a passive optical distribution network based on space division multiplexing (SDM) for parallel propagation[2].

The software defined networking (SDN) control of the resources for optical beamforming and its integration in the network function virtualization (NFV) service management and orchestration (MANO) for beyond 5G fronthaul networks brings many challenges that have to be properly addressed[3]. First, ARoF transceivers and OBFN systems must be integrated in the optical SDN controller to provide OBF connectivity services. Moreover, the NFV MANO must integrate the optical SDN controller, together with the RRHs and ARoF BBUs as physical network functions (PNF) in order to provide beyond 5G network services.

Target optical beamforming scenario

The considered 5G fronthaul scenario with OBF is shown in Fig. 1 and includes separate OBFNs for down- and uplink. The OBFN for the uplink direction is a coherent OBFN, where beamforming is achieved through optical phase shifting and subsequent heterodyning with an optical reference signal, translating the optical phase shift into electrical phase shifts[2]. By implementing a 4×4 Blass matrix structure of tuneable phase shifts, the coherent OBFN allows concurrent transmission of 4 independent beams from a single OBFN and antenna array. The corresponding ARoF transmitter at the CO features 4 channels corresponding to the 4 beams. The OBFN maps each of these input channels to each of its outputs with different differential delays, allowing independent steering and shaping of the beams. The outputs signals from the OBFN are transmitted over a multi-core fibre (MCF) to the RU where optical heterodyning at the 4 channel ARoF receiver converts the signal to mm-wave, ready for radiation via the RRH with a 4 element antenna array.

The OBFN chosen for the uplink is an incoherent OBFN, implementing a similar Blass matrix structure, but based on true time delays and optical filters. In this case the ARoF transmitter features four lasers spaced at 200 GHz, each modulated with an IF signal obtained from the RRH after separate downconversion of the signals received from the 4 element antenna array. Through its matrix of true time delays, the OBFN maps the four inputs signals to the four output signals with different temporal alignment on each output, resulting in constructive interference only for a single beam direction on each output. The output signals are transmitted over the MCF to

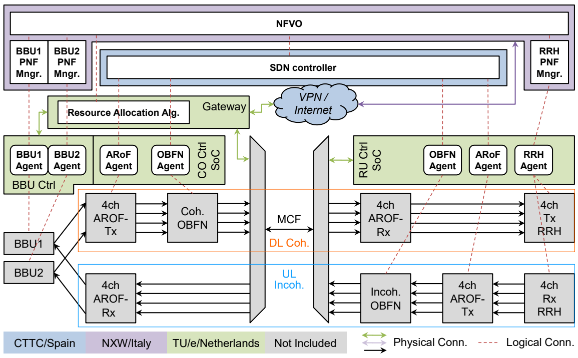

Fig. 1: SDN/NFV-enabled fronthaul scenario with optical beamforming and distributed control implementation.

the CO and received by a 4 channel IF ARoF receiver. In both cases the ARoF BBU performs 5G NR OFDM signal processing and generation or analysis for down- and uplink respectively.

OBF SDN connectivity service

The control of the OBF fronthaul network is delegated to the optical SDN controller, under the global coordination of the NFV orchestrator (NFVO), as shown in Fig. 1. The optical SDN controller is responsible for the lifecycle management of the OBF connectivity services. It is performed by configuring and monitoring the ARoF transceivers and OBFN systems (both coherent and incoherent) through the respective SDN agents. The interface between the NFVO and the SDN controller is based on the transport API (TAPI) specification. In general, the SDN controller generates a TAPI context for the NFVO. A TAPI context is defined by a set of service interface points (SIPs), which enables the NFVO to request connectivity services between pairs of endpoints to the SDN controller. We have defined a new TAPI data model for the OBF service (tapi-obfn.yang) that is available in a public repository[4]. For this, an additional protocol layer qualifier (*tapi-obfn:PHOTONIC_LAYER_QUALIFIER_OBFN*) within the *PHOTONIC_MEDIA* layer has been introduced. The model augments key TAPI entities and objects in support of OBF.

In particular, SIPs are augmented with the supported wavelength band and grid, supported beams (e.g., 4), supported upper and lower angle (e.g., 60º, -60º), supported max and min width (e.g., 60º, 20º). The *connectivity-service* and the *connection-end-point-spec* are augmented with the requested/configured reference wavelength, and a list of beams, specifying for each beam the status (on/off), the offset-angle-X, offset-angle-Y, and width. It is worth highlighting that for the

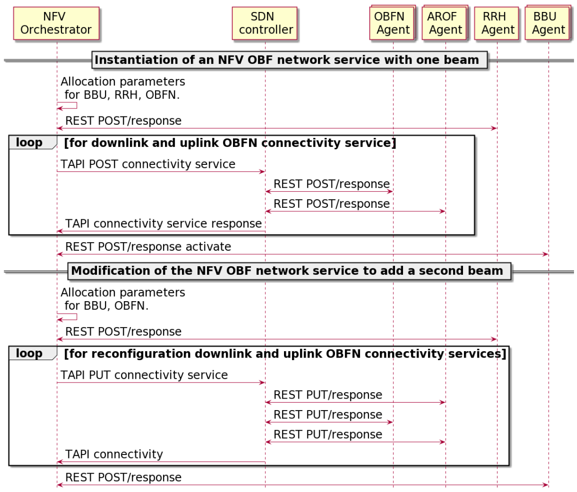

Fig. 2: Workflow for the instantiation and modification of an OBF NFV network service

coherent OBFN (i.e., downlink), each channel of the ARoF transmitter corresponds to one beam and all share the same wavelength, for the incoherent OBFN (i.e., uplink) all channels are always activated and are separate by 200 GHz. Transport across the MCF requires 4 cores for downlink independent of the number of beams as beamformed signals are transported, while for uplink cores can be enabled independently as more beams are added. We consider unidirectional connectivity services, therefore the OBF connectivity service parameters for the downlink and uplink are defined separately in two different calls.

OBF NFV network service

The NFV orchestrator is responsible for the lifecycle management of the overall OBF NFV network services. Fig. 2 shows the workflow involved in the instantiation of a complete NFV network service in the OBF fronthaul, involving the BBUs and RRHs. Upon receiving an NS instantiation request, the NFVO computes the resource allocation solution using the resource allocation algorithms. The NFVO then feeds the resource allocation algorithm with the service constraints and the infrastructure resource information. The outcome of the resource allocation algorithms determines the OBFN resources (i.e., reference wavelength, and offset angles and width for each beam to setup the OBF connectivity service), and the RRH and BBU devices to be used and their configuration parameters. The following step involves the configuration of the RRH, which is configured through the RRH PNF manager (as shown in Fig. 1) with the settings selected by the allocation algorithm (e.g., the power amplifier gains). Once the RRH is configured, the NFVO requests the provisioning of the OBF connectivity service for the downlink and uplink. For this, the NFVO selects the SIPs associated to the involved BBUs and RRHs and issues a TAPI POST request containing the selected SIPs, the obtained reference wavelength and the array of the offset angles (X and Y) and width for each beam specified in the *connectivity-service*. The optical SDN controller maps the SIPs to the specific ARoF and OBFN devices and starts the configuration through the respective agents, first configuring the OBFN coherent/incoherent devices and then the ARoF transceiver. Once configured, the NFVO requests the provisioning of the OBF connectivity service for the uplink, following the same procedure. Once both the downlink and uplink OBF connectivity services are provisioned, the NFVO configures the involved BBUs through the BBU PNF manager that send the corresponding configuration (e.g., 5G NR waveform parameters provided by the resource allocation) to the BBU PNF agent. It is required to configure as many BBUs as beams are activated. At this point, OBF NFV network service is instantiated.

The next step in the workflow is to modify the established OBF NFV network services to add new beams or remove existing ones. If new beams are requested, the NFVO requests to the resource allocation algorithm the information of required resources and updates the RRH configuration. Then, the NFVO requests to the SDN controller the modification of the existing OBF connectivity services, both for the downlink/uplink, specifying the new configuration of the beams in the *connectivity-service*. The optical SDN controller configures the coherent/incoherent OBFN devices with the new beams, and the ARoF transceivers. After that, the NFVO configures the required BBUs.

Experimental validation

The various SDN/NFV components are deployed in a geographically distributed fashion as shown in Fig. 1, with the NFVO and PNF managers in one location, the SDN controller in another and the agents and resource allocation algorithm service in a third location, with the agents deployed on system-on-chip boards ready for direct integration with the ARoF BBUs, ARoF fronthaul transmitters, OBFNs and RRHs. The different locations are linked through a VPN hosted in the same location as the SDN controller, with a dedicated gateway providing connectivity towards all agents and a fibre-based control channel between the CO and RU ensuring control connectivity across the fronthaul link. It should be noted that the remainder of the fronthaul hardware for simplicity was not included in this experiment.

Step	**Resource Alloc.** [s]	**RRH Conf.** [s]	**DL Connectivity** [s]	**UL Connectivity** [s]	**BBU** [s]	**Overall** [s]
Provisioning	2.4	0.4	1.1	0.9	0.4	22.3
Add 2nd beam	1.5	0.7	0.7	0.9	0.6	20.1
Rem 2nd beam	—	0.8	0.7	0.7	0.6	12.3
Deletion	—	0.6	1.0	0.8	0.6	12.4

Tab. 1: Measured timing for the validated workflow steps.

In this scenario, we performed several time measurements of the overall OBF NFV network service provisioning with 1 beam (i), modification of the OBF NFV network service adding a second beam (ii) and removing the first beam (iii), and deleting the OBF NFV network service, as detailed in Table 1. The overall OBF NFV network service delay is the time required to the NFVO to complete the lifecycle management workflow taking into account all the internal mechanisms of the NFVO. It is in the range of 20-22s for provisioning/modification, and 12s for deletion. Additionally, we also provide the contribution in the overall OBF NFV network service time for the resource allocation service, RRH PNF mangement, OBF SDN connectivity service for downlink and uplink, and BBU PNF managment. The values for each of these items were obtained using packet traces and the internal logs of the NFVO.

Conclusions

This paper has experimentally validated the proposed SDN/NFV control architecture for dynamic management of optical beamforming connectivity and network services for beyond 5G fronthaul.

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