Software Defined Applications in Cellular and Optical Networks

by

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ABSTRACT

Small wireless cells have the potential to overcome bottlenecks in wireless access through the sharing of spectrum resources. A novel access backhaul network architecture based on a Smart Gateway (Sm-GW) between the small cell base stations, e.g., LTE eNBs, and the conventional backhaul gateways, e.g., LTE Servicing/Packet Gateways (S/P-GWs) has been introduced to address the bottleneck. The Sm-GW flexibly schedules uplink transmissions for the eNBs. Based on software defined networking (SDN) a management mechanism that allows multiple operator to flexibly inter-operate via multiple Sm-GWs with a multitude of small cells has been proposed. This dissertation also comprehensively survey the studies that examine the SDN paradigm in optical networks. Along with the PHY functional split improvements, the performance of Distributed Converged Cable Access Platform (DCCAP) in the cable architectures especially for the Remote-PHY and Remote-MACPHY nodes has been evaluated. In the PHY functional split, in addition to the re-use of infrastructure with a common FFT module for multiple technologies, a novel cross functional split interaction to cache the repetitive QAM symbols across time at the remote node to reduce the transmission rate requirement of the fronthaul link has been proposed.

I dedicate this dissertation to my lovely mother Shobharani D., father Shivanna T. S. and younger brother Dr. Harshith Thyagaturu, who always stood by me and supported all my decisions, to my grandmother and in her memory Puttamma P., who would have been very proud to see me graduate with a Ph.D., finally to my close and very special friends Deepak Muckatira, Praveen Janarthanan, Ramya Ramasubramanian and Swathi Balakrishna, who selflessly showed unconditional love and support.

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CHAPTER 1

SDN BASED SMART GATEWAYS (SM-GWS) FOR MULTI-OPERATOR SMALL CELL NETWORK MANAGEMENT

1.1 INTRODUCTION

1.1.1 Motivation: Small Cells

Recent wireless communications research has examined the benefits of splitting the conventional cells in wireless cellular communications into small cells for supporting the growing wireless network traffic. Small cells can coexist with neighboring small cells while sharing the same spectrum resources [20], and are thus an important potential strategy for accommodating wireless network traffic growth [21]. Small cells are also sometimes referred to as "femto" cells in the context of the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) wireless standard; we use the general terminology "small" cells throughout. However, small cells pose new challenges, including interference coordination [22], backhaul complexity [23, 24], and increased network infrastructure cost [25]. In this article [26] we propose a solution to reduce the infrastructure cost and complexity of backhaul access networks supporting small cells.

Small cell networks are expected to be privatively owned [27]. Therefore it is important to enable usage flexibility and the freedom of investment in the new network entities (e.g., gateways and servers) and the network infrastructures (e.g., switches and optical fiber) by the private owners of small cells. While a plethora of studies has examined advanced enhanced Node B (eNB) resource management, e.g., [28–30], the implications of small cell deployments for backhaul gateways have largely remained unexplored [31]. Generally, backhaul access networks that interconnect small cell deployments with LTE gateways can employ a wide variety of link layer (L2) technologies, including SONET/SDH, native Ethernet, and Ethernet over MPLS [32–34]. In order to accommodate these heterogeneous L2 technologies, cellular LTE network interfaces, such as S1 and X2 interfaces, are purposefully made independent of the L2 technology between small cell deployments and gateways. Due to the independent nature of L2 technologies, a dedicated link with prescribed QoS, which can support the fundamental operations of cellular protocols, must be established for each interface connection [35]. Statistical multiplexing is then limited by the aggregate of the prescribed QoS [36, 37] requirements and only long-term reconfigurations, e.g., in response to deployment changes, can optimize the backhaul transmissions [38]. Present wireless network deployments based on the 3GPP LTE standard do not provide feedback from the eNBs to a central decision entity, e.g., an SDN orchestrator, which could flexibly allocate network resources based on eNB traffic demands. Thus, present wireless backhaul architectures are characterized by (*i*) essentially static network resource allocations between eNBs and operator gateways, e.g., LTE Servicing/Packet Gateways (S/P-GWs), and (*ii*) lack of coordination between the eNBs and the operator gateways in allocating these network resources, resulting in under-utilization of the backhaul transmission resources. Additionally, exhaustion of available ports at the operator gateways can limit the eNB deployment in practice.

The static resource allocations and lack of eNB-gateway cooperation are highly problematic since the aggregate uplink transmission bitrate of the small cells within a small geographic area, e.g., in a building, is typically much higher than the uplink transmission bitrate available from the cellular operators. Thus, small cell deployments create a bottleneck between the eNBs and the operator gateways. For instance, consider the deployment of 100 small cells in a building, whereby each small cell supports 1 Gbps uplink transmission bitrate. Either each small cell can be allocated only

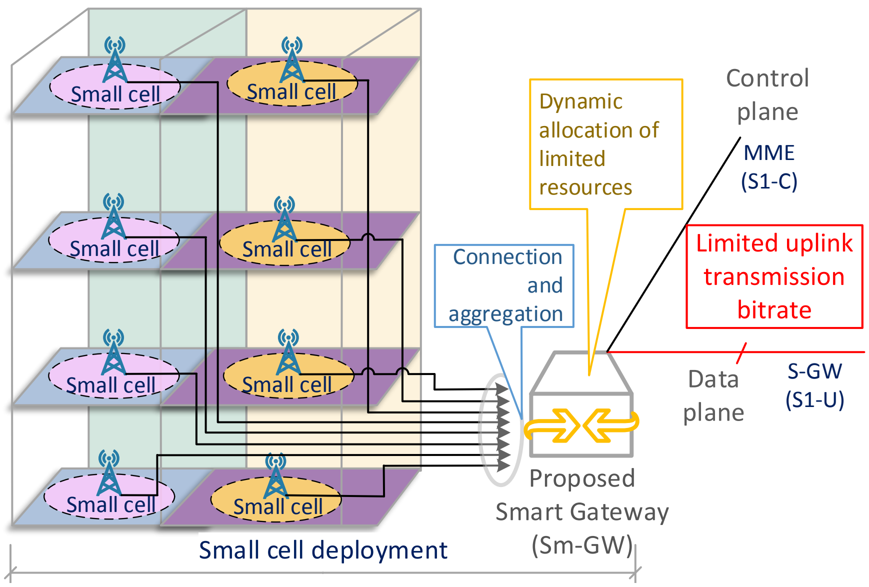


Figure 1.1: The proposed smart gateway (Sm-GW).

one hundredth of the operator bitrate for this building or the operator would need to install 100 Gbps uplink transmission bitrate for this single building, which would require cost-prohibitive operator gateway installations for an organization with several buildings in a small geographical area. However, the uplink transmissions from the widespread data communication applications consist typically of short high-bitrate bursts, e.g., 100 Mbps bursts. If typically no more than ten small cells burst simultaneously, then the eNBs can dynamically share a 1 Gbps operator uplink transmission bitrate. An additional problem is that with the typically limited port counts on operator gateways, connections to many new small cells may require new operator gateway installations. An intermediate Sm-GW can aggregate the small cell connections and thus keep the required port count at operator gateways low.

1.1.2 Overview of Network Management with SDN-based Sm-GW

We present a new backhaul network framework for supporting small cell deployments based on a new network entity, the Smart GateWay (Sm-GW). Consider an exemplary small cell deployment throughout multiple buildings of a university. Each building has hundreds of small cells that are flexibly connected to an Sm-GW, as illustrated in Fig. 1.1. Multiple Sm-GWs are then connected to core networks, i.e., the S-GWs and P-GWs, of multiple cellular operators via physical links (e.g., optical or microwave links) [39–46], as illustrated for a single Sm-GW in Fig. 1.2. An SDN orchestrator owned by the university manages the cellular infrastructure of the entire university. The SDN orchestrator coordinates the resource allocations from the operators to the Sm-GWs.

The main original contributions of this article are:

1. A novel comprehensive Smart Gateway (Sm-GW) architecture and protocol framework that accommodates a flexible number of eNBs while reducing the requirements at the operator's core, e.g., at LTE S-GW and MME. The Sm-GW physically and logically aggregates the eNB connections so that a set of eNBs appears as a single virtual eNB to the operator gateways, see Section 4.2.

2. A Sm-GW scheduling framework to flexibly share the limited uplink transmission bitrate among all the small cell eNBs connected to an Sm-GW, see Section 1.4.

3. An adaptive SDN-based multi-operator management framework that dynamically shares the uplink transmission bitrates of multiple operators among the Sm-GWs. An SDN orchestrator dynamically coordinates the sharing among the Sm-GWs, the transport network connecting the Sm-GWs to the operator gateways, and the operator gateways, see Section 1.5.

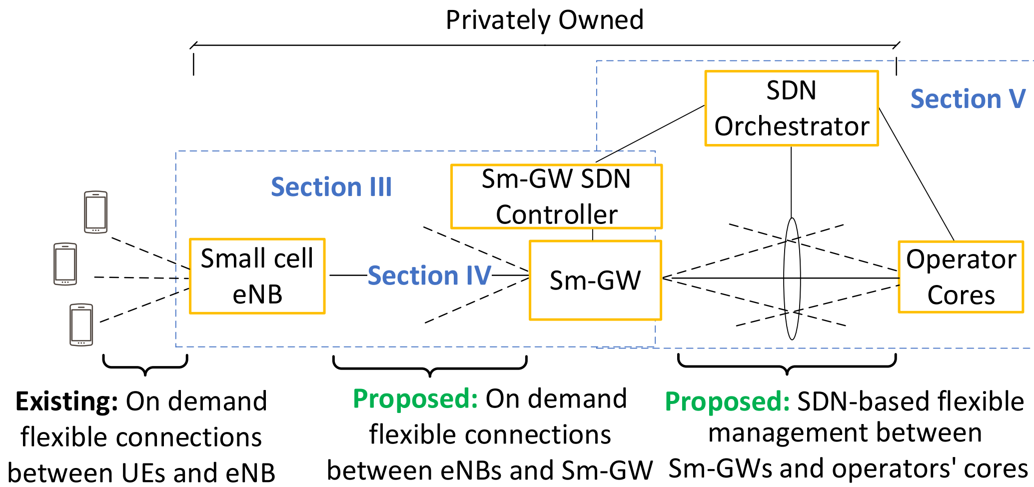


Figure 1.2: The Smart Gateway (Sm-GW) architecture.

1.1.3 Related Work

Recently proposed SDN based backhaul architectures, such as CROWD [47, 48], iJOIN [49], U-WN [50], Xhaul [51], the multi-tiered SDN based backhaul architecture [52], and similar architectures [53–58], are revolutionary designs proposing new cellular infrastructure installations. In contrast, our proposed SDN-based Sm-GW enables the softwarization of *existing* cellular infrastructures consisting of eNBs and conventional operator gateways, such as the S/P-GW in LTE core networks. The proposed Sm-GW is inserted in the existing backhaul infrastructure to inter-network and co-exist with the existing LTE network core entities, such as the S/P-GW.

SDN based backhaul architectures with centralized interference coordination have been proposed in [59–61]. The SDN controller in these architectures maintains a global database of spectrum resources [62] and dynamically assigns the resources to base stations so as to minimize the mutual interference among base stations in dense deployments. We note that wireless interference is a localized phenomenon. Therefore, a base station is most affected by its neighboring base stations in dense deployments. The centralized interference coordination techniques in [59–61] are complementary to our proposed Sm-GW architecture in that they can be implemented at the Sm-GW instead of the SDN controller/orchestrator.

Schedulers at the eNB allow multiple user equipment (UE) devices to share the wireless resources at the eNB. For example, the LTE standard medium access control (MAC) protocol [63] coordinates the scheduling of wireless resources between an eNB and multiple UEs. Generally, most wireless resource scheduling studies to date have focused on the sharing of the wireless resources at a given single eNB. For instance, quality of service (QoS) aware uplink scheduling and resource allocation at a given single small cell eNB in an LTE network have been examined in [64]. In contrast, we propose a novel scheduling framework at the Sm-GW based on uplink transmission bitrate requests from *multiple eNBs*, i.e., we propose the sharing of the backhaul network resources among multiple eNBs.

A similar sharing of network resources among small cell base stations has been studied in [65]. Specifically, the H-infinity scheduler for limited capacity backhaul links [65] schedules the traffic in the downlink. The centralized H-infinity scheduler focused on buffer size requirements at the base stations in the small cell networks. In contrast, we focus on the *uplink* traffic from the eNBs to the Sm-GW. To the best of our knowledge, we propose the first network protocol framework for the uplink transmissions from multiple eNBs to the operator gateways in the context of LTE small cells. We note that our Sm-GW framework is complementary to several recently studied resource allocation mechanisms in cellular networks. For instance, D2D resource allocation through traffic offloading to small cell networks has been studied in [66]; this D2D approach can be readily supported by our proposed Sm-GW. Coordinated scheduling [67–70] in the context of small cells with dynamic cell muting to mitigate

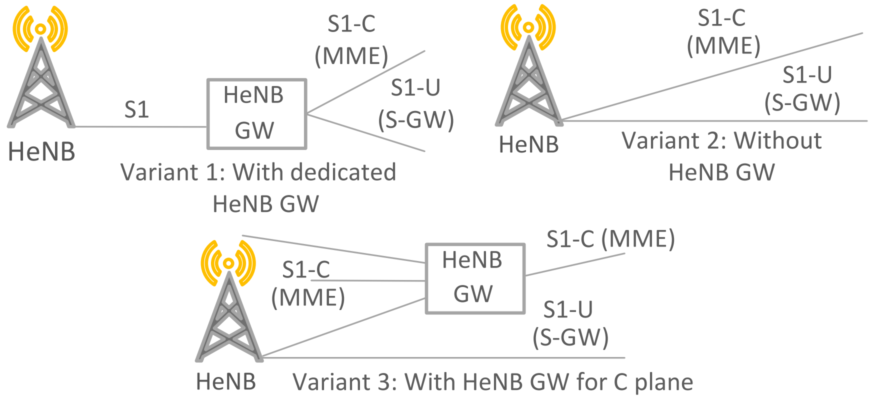


Figure 1.3: HeNB architectural models in 3GPP LTE.

the interference has been discussed in [71]. The cell muting technique can be further extended based on our approach of traffic scheduling to eNBs. A flexible wireless resource allocation mechanism based on the SDN programmability of traffic flows from a single UE device to multiple base stations in dense small cell networks has been examined in [72]. The offloading of UE traffic for efficient traffic management in small cell networks has been examined in [73]. In contrast, we propose an SDN-based multi-operator resource allocation mechanism that allocates limited backhaul link capacities to multiple Sm-GWs (which in turn can flexibly allocate the capacities to multiple eNBs). The UE to eNB communication approach from [72] and UE traffic offloading [73] are thus complementary to our eNB to Sm-GW and Sm-GW to S/P GW network management approaches.

1.2 BACKGROUND: CONVENTIONAL LTE SMALL CELL BACKHAUL

In this section we describe the conventional architectural model for Home-eNodeB (HeNB) access networks [74] and the network sharing mechanism in 3GPP LTE. HeNBs are the small cell base stations of the LTE standard. We use the general terminology “eNB” to denote all types of small cell base stations.

1.2.1 HeNB Architectural Models in 3GPP LTE

In Figure 1.3 we show the 3GPP HeNB architectural models: 1) with dedicated HeNB-GateWay (HeNB-GW), 2) without HeNB-GW, and 3) with HeNB-GW for the control plane.

1.2.1.1 With Dedicated HeNB-GW

With a dedicated HeNB-GW, communication between the HeNB and the HeNB-GW is secured by a mandatory security gateway (Se-GW) network function. The HeNB-GW aggregates the control plane connections (S1-MME) and user plane connections (S1-U) of all HeNBs connected to the HeNB-GW to a single control and user plane connection. The HeNB gateway appears as a single eNB to the outside entities, such as S-GW and MME. In a similar way, the HeNB-GW appears as both an S-GW and an MME to the eNBs connected to the HeNB-GW. The numbers of ports required at the MME and S-GW are reduced through the aggregation at the HeNB-GW. Our proposed Sm-GW architecture is similar to the dedicated HeNB-GW architecture, in that the Sm-GW aggregates the eNBs connections both physically and logically. In addition, our Sm-GW flexibly allocates uplink transmission bitrates to small cell eNBs (see Section 1.4) and allows for the adaptive allocation of operator uplink transmission bitrates to the Sm-GW by the SDN orchestrator (see Section 1.5).

1.2.1.2 Without HeNB-GW

Deployments of HeNBs without the HeNB-GWs increase the requirements on the S-GW and MME to support large numbers of connections. Large deployments of small cells without gateway aggregation at the HeNBs would greatly increase the total network infrastructure cost.

1.2.1.3 With HeNB-GW for the Control Plane

HeNB control plane connections are terminated at the HeNB-GW and a single control plane connection is established from the HeNB gateway to the MME. Although the number of connections required at the MME is reduced due to the control plane aggregation at the HeNB-GW, data plane connections are still terminated directly at the S-GW, increasing requirements at the S-GW. The Se-GW typically secures the communication to and from the HeNB. In contrast, our proposed Sm-GW terminates all the control and data connections from HeNBs.

1.2.2 3GPP Network Sharing

Network sharing was introduced by 3GPP in Technical Specification TS 23.951 [75] with the main motivation to share expensive radio spectrum resources among multiple operators. For instance, an operator without available spectrum in a particular geographic area can offer cellular services in the area through sharing the spectrum of another operator. In addition to spectrum sharing, 3GPP specifies core network sharing among multiple operators through a gateway core network (GWCN) configuration [75]. GWCN configurations are statically pre-configured at deployment for fixed pre-planned core network sharing. Thus, GWCN sharing can achieve only limited statistical multiplexing gain as the sharing is based on the pre-configured QoS requirements of the eNB interface connections and not on the varying eNB traffic demands. Also, the GWCN configuration lacks a central entity for optimization of the resource allocations with global knowledge of the eNB traffic demands. In contrast, our Sm-GW framework includes a central SDN orchestrator for optimized allocations of backhaul transmission resources according to the varying eNB traffic demands (see Section 1.5).

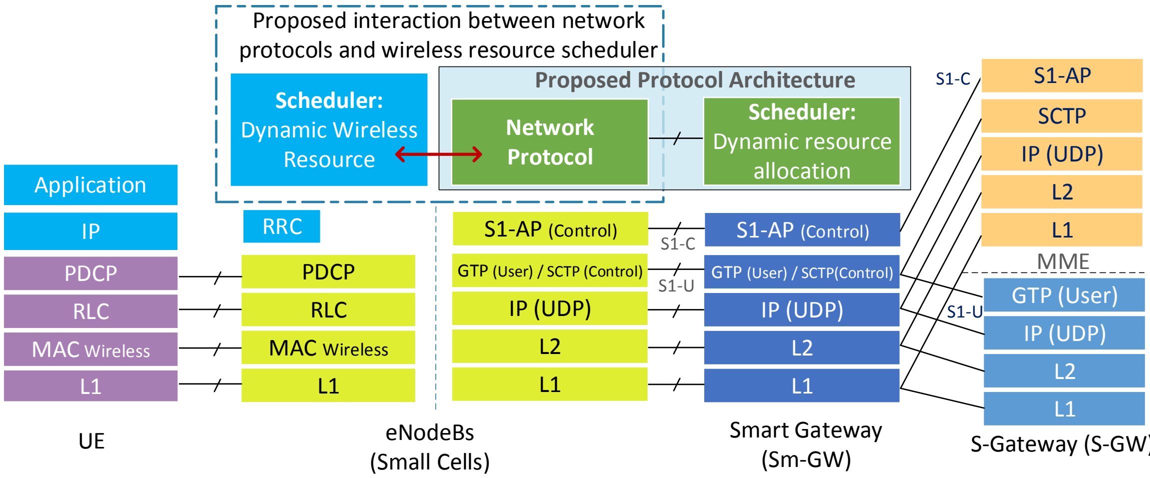


Figure 1.4: Illustration of proposed protocol mechanisms at eNB, Sm-GW, and S-GW.

1.3 PROPOSED SMART GATEWAY (SM-GW)

In this section we introduce the proposed Smart Gateway (Sm-GW) network architecture for existing LTE deployments. We describe the fundamental protocol mechanisms and interfaces that integrate the proposed Sm-GW into the conventional LTE protocols.

1.3.1 LTE Protocol Modifications

Fig. 1.4 illustrates the proposed protocol mechanisms between a set of N_s eNBs and a given Sm-GW s.

1.3.1.1 eNB

At the eNB, we newly introduce the eNB-to-Sm-GW reporting protocol, which operates on top of the GPRS tunneling protocol (GTP) [76] and stream control transmission protocol (SCTP). The reporting protocol (*i*) evaluates the required uplink transmission bitrate, and (*ii*) sends the bitrate request messages to the Sm-GW. The reporting protocol formulates the operator specific uplink transmission bitrate requests based on the requests of the UEs that are connected via the eNB to multiple operators o, $o = 1, 2, \ldots, O$.

The eNB wireless resource scheduler is responsible for the sharing of wireless resources between the eNB and the UEs. The eNB wireless resource scheduler ensures that only the resources available at the eNB are granted to the UEs. UEs periodically send buffer status reports (BSRs) to the eNB which they are connected to. Therefore, the eNB-to-Sm-GW reporting protocol can estimate the UE traffic requirements by interacting with the wireless resource scheduler.

1.3.1.2 Smart Gateway (Sm-GW)

The protocol stack at the Sm-GW is similar to the HeNB-GW protocol stack. However, in the Sm-GW, an additional eNB coordination protocol, a scheduler for the dynamic resource allocation, and SDN capabilities are introduced.

The eNB coordination protocol collects request messages from eNBs. The eNB uplink transmission grants are sized based on the eNB requests and the available Sm-GW resources according to the Sm-GW scheduling described in Section 1.4. The eNB coordination protocol sends grant messages to all eNBs within a reasonable processing delay.

S1 based handovers for the downlink transmissions are typically anchored at the S-GW. (For the uplink transmissions, an anchoring, or buffering of packets, at a network entity, e.g., eNBs or S-GW, is not required.) We emphasize that the Sm-GW will be transparent to all the downlink packets from the S-GW and hence not be limited by the network protocol scheduler. This ensures that the S1 based handover mechanisms at the S-GW and eNBs continue to function normally.

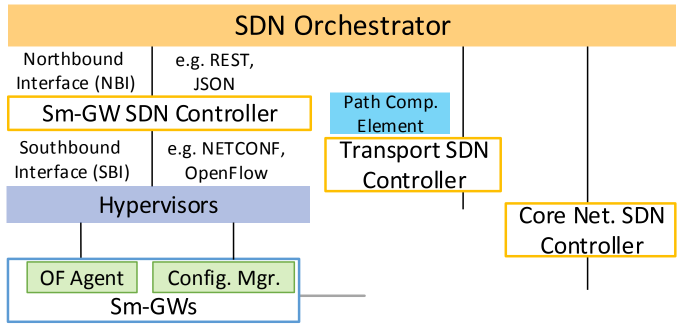


Figure 1.5: Illustration of Sm-GW embedding in the SDN ecosystem.

1.3.1.3 SDN Operations of Sm-GW

SDN Infrastructure The Sm-GW SDN capabilities can be provided by an OpenFlow (OF) agent and/or a configuration manager at each Sm-GW, as illustrated in Fig. 1.5. OpenFlow is a popular protocol for the southbound interface (SBI) and can be employed on the SBI between the Sm-GW SDN controller and Sm-GW. The OpenFlow agent supports OpenFlow SDN functionalities at the Sm-GW, making the Sm-GW configurable through the OpenFlow protocol. The Sm-GW configuration manager can be controlled by the Sm-GW SDN controller, e.g., through the NETCONF (or OpenFlow) SBI, to dynamically reconfigure the Sm-GW.

The Sm-GW SDN controller configures the Sm-GWs to enable the internal LTE X2 tunnel interfaces among all connected small cell eNBs, as elaborated in Section 1.3.1.4. Also, the Sm-GW SDN controller manages the external LTE X2 and S1 interfaces at the Sm-GW through tunnel establishments to the external LTE network core entities, i.e., MMEs and S/P-GWs.

Whereas the conventional LTE transport network between the eNBs and S/P-GWs is configured with static MPLS/IP paths [35], the flexible Sm-GW operation requires a flexible transport network, that is controlled by a transport SDN controller, as illustrated in Fig. 1.5. The flexible transport network can, for instance, be implemented through a Software Defined Elastic Optical Network (SD-EON) [77, 78].

Sm-GW Virtualization The SM-GW can support a variety of virtualization strategies, e.g., to provide independent virtual networks for different operators. One example virtualization strategy could let the Sm-GWs abstract the connected eNBs. Sm-GWs could then be abstracted by a hypervisor [79–82] that intercepts the SBI, as illustrated in Fig. 1.5. Based on the operator configurations that are sent via the SDN orchestrator to the Sm-GW SDN controller, resources at the Sm-GWs and the small cell eNBs (which are privately owned by an organization [27]) can be sliced to form operator-specific virtual networks of Sm-GWs and eNBs. The configuration manger at each Sm-GW can allocate resources to each of these virtual networks.

From the operator perspective, the Sm-GW virtualization [83] essentially allows multiple operators to share the physical small cell infrastructure of Sm-GWs and eNBs. Thus, simultaneous services can be enabled to large UE populations that belong to multiple operators, i.e., that have contracts with multiple operators, while using the same physical small cell infrastructure. Existing conventional cellular deployment structures do not support the infrastructure sharing among multiple operators.

SDN Orchestration The SDN orchestrator coordinates the network management across multiple domains of Sm-GWs (whereby each Sm-GW domain is controlled by its own Sm-GW SDN controller), transport networks, and core networks. The SDN orchestrator implements the multi-operator management introduced in Section 1.5 and configures the Sm-GWs and transport networks based on global multi-operator network optimizations. For example, the SDN orchestrator communicates with the path computation element (PCE) SDN application on the transport SDN controller. The PCE dynamically evaluates the label switched paths, such as MPLS/IP paths, so as to flexibly enable and reconfigure the transport network [77, 78].

1.3.1.4 LTE X2 Interfaces of eNBs with Sm-GW

X2 interfaces enable critical functionalities in LTE small cells, such as X2-based handover as well as interference coordination and mitigation. Typically, each eNB connected to a given Sm-GW pertaining to an operator shares the same MME; thus, each eNB needs an X2 interface to all other eNBs within the same MME coverage area, the so-called tracking area. Hence, eNBs connected to an Sm-GW must be interconnected with X2 interfaces.

To External Macro-eNBs X2 traffic flows destined to eNBs located outside the scope of an Sm-GW (typically to a macro-eNB) are not be limited by the scheduler at the Sm-GW. X2 packets flow out of Sm-GW into the backhaul (i.e., to an S-GW) as they originate at the eNBs. The Sm-GW appears as an external router (or gateway) to the X2 external interfaces.

To Internal Small-eNBs The Sm-GW appears as a simple bridge or a router to the internal X2 interfaces, routing the internal X2 packets within. Therefore, the scheduler at the Sm-GW does not limit any X2 packets. For small cell deployments, an eNB can have multiple neighboring eNBs in the tracking area; these neighboring eNBs need to be interconnected with each other with X2 connections. On the order of $O(N(N-1))$ dedicated links would be required to interconnect the X2 interfaces of N eNBs in the tracking area in a full mesh topology. In contrast, a star topology with the Sm-GW at the center requires only $O(N)$ connections to connect each eNB to the Sm-GW. In summary, in our Sm-GW architecture, the Sm-GW manages the

X2 interfaces of all the internal small cell eNBs, thus eliminating the distributed management of X2 interfaces at each eNB.

1.3.1.5 Authentication of Sm-GW with EPC Core

Typically HeNBs use IPSec tunneling for their security and encryption, which creates overhead. If Sm-GWs are authenticated, the HeNBs would no longer need IPsec tunneling. Specifically, upon boot-up, the Sm-GW is authenticated with an LTE Evolved Packet Core (EPC) so as to eliminate the need for a network security-gateway (Se-GW) function or IPsec tunneling between the eNBs and the P-GWs. Critical cellular network functions, such as security, authentication, and reliability, require additional effort to be enabled in WiFi networks. WiFi Passpoint [84] (Hotspot 2.0) aims at providing an experience similar to cellular connectivity in WiFi networks by providing the cellular authentication mechanisms. With the authentication of Sm-GWs, the simplicity of WiFi networks can be achieved by the small cell cellular networks.

1.3.2 Downlink vs. Uplink Communication

1.3.2.1 Downlink Packets at the Sm-GW

Traffic flows in the conventional downlink path from an S/P-GW to an eNB are typically sent at rates that do not exceed the wireless transmission rates from the eNB to the UE devices. Thus, as long as the link rates from the S/P-GW to the inserted Sm-GW and from the Sm-GW to the eNB are at least as high as the conventional S/P-GW to eNB links, the Sm-GW can be transparent to the downlink packets from the S/P-GW.

1.3.2.2 Uplink Packets at Sm-GW

In contrast to the downlink data traffic, the uplink data traffic from the eNBs to an Sm-GW needs to be regulated as the traffic flows from all the eNBs terminating at the

Sm-GW can overwhelm the outgoing link towards the operator S-GW. Enforcing QoS strategies and fairness among eNBs requires scheduling of the uplink packet traffic arriving from the eNBs at an Sm-GW. Therefore, our focus is on frameworks for the uplink transmission scheduling of the communication (*i*) from eNBs to an Sm-GW (Section 1.4), and (*ii*) from Sm-GWs to S-GWs (Section 1.5).

1.4 PROPOSED SM-GW SCHEDULING FRAMEWORK

1.4.1 Purpose

The main purpose of the Sm-GW scheduling framework is to maximize the utilization of the network resources, and to ensure fair uplink transmission service for all eNBs connected to an Sm-GW. Without scheduling, highly loaded eNBs can impair the service for lightly loaded eNBs connected to the same Sm-GW. When many eNBs are flexibly connected to an Sm-GW, traffic bursts from heavily loaded eNBs can overwhelm the queue of an Sm-GW, resulting in excessive packet drops and high delays, even for lightly loaded eNBs. On the other hand, with scheduling, a large number of eNBs can be flexibly connected to the Sm-GW while ensuring prescribed QoS and fairness levels. Each eNB can possibly have a different service level agreement. The Sm-GW allows for the flexible deployment of a wide variety of scheduling algorithms. We outline two classes of Sm-GW scheduling algorithms, and illustrate an elementary algorithm for each class.

1.4.2 Configuration Adaptive Scheduling

Configuration adaptive scheduling adapts the scheduling, i.e., the allocation of uplink transmission bitrates, according to the number of eNBs connected to a given Sm-GW. The Sm-GW tracks the number of connected eNBs and sends a configuration message to all eNBs in the event of a change in connectivity at the Sm-GW, i.e., addition of new eNB or disconnection of existing eNB. More specifically, consider N_s eNBs at a

Table 1.1: Summary of Notation of Sm-GW Network Management

Sm-GW Sched. Framework (Sm-GW $\leftrightarrow$ eNBs), Sec. 1.4	
N_s	Number of small cell eNBs at Sm-GW s
G_{so}	Available uplink transm. bitrate [bit/s] from Sm-GW s to operator o
W	Duration [s] of scheduling cycle
Γ_{so}	$= G_{so}W/N_s$, Max. eNB uplink transm. data amount [bit] per cycle with equal sharing
ρ_{son}	Data amount [bit] that eNB n at Sm-GW s wants to transmit to operator o in a cycle, i.e., request by eNB n
γ_{son}	Data amount [bit] that eNB n at Sm-GW s is allowed to transmit to operator o in a cycle, i.e., grant by Sm-GW s
SDN Based Multi-Operator Managm. Framework, Sec. 1.5 (Sm-GWs $\leftrightarrow$ Operator Gateways)	
o	Index of operators, $o = 1, 2, \ldots, O$
s	Index of Sm-GWs, $s = 1, 2, \ldots, S$
R_{so}	Smoothed uplink transmission bitrate [bit/s] request from Sm-GW s to operator o
K_o	Max. available uplink transm. bitrate through operator o
G_{so}	Granted uplink transm. bitrate from Sm-GW s to operator o
X_{so}	Actual uplink traffic bitrate from Sm-GW s to operator o

given Sm-GW s that has been allocated the uplink transmission bitrate G_{so} [bit/s] toward a given operator o (through the coordination techniques in Section 1.5).

An elementary equal share scheduling shares the available uplink transmission bitrate at the Sm-GW toward a given operator o equally among all eNBs connected to the Sm-GW. Each eNB n, $n = 1, 2, \ldots, N_s$, can then transmit at most $\Gamma_{so} = G_{so}W/N_s$ [Byte] of traffic during a cycle of duration W [seconds]. The traffic amount limit Γ_{so} and cycle duration W are sent to the eNBs as a part of the initial configuration

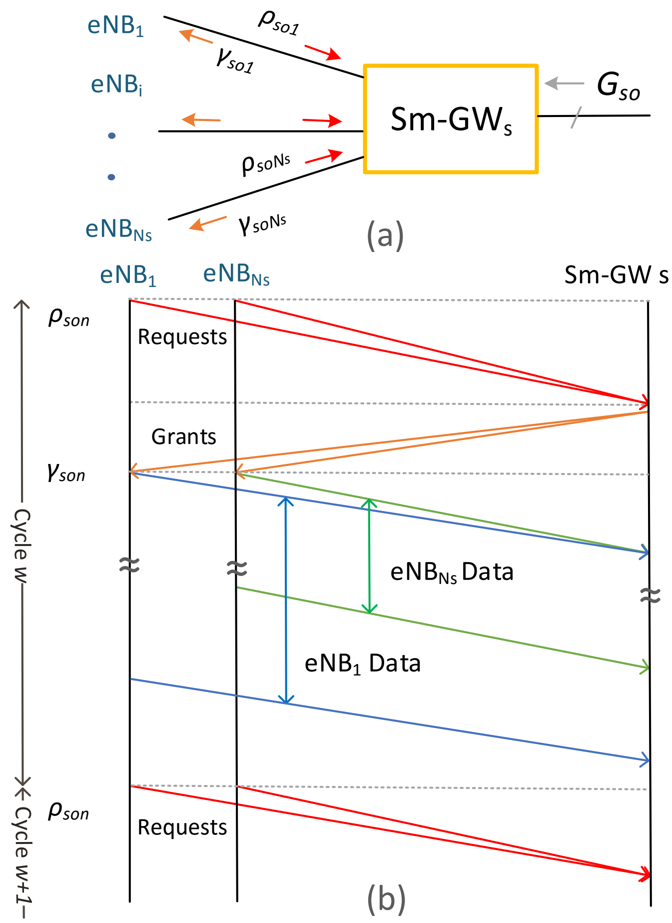


Figure 1.6: Illustration of traffic adaptive Smart Gateway (Sm-GW) scheduling.

message. Each eNB schedules the uplink transmissions such that no more than Γ_{so} [Byte] of traffic are send in a cycle of duration W [seconds].

The simple equal share scheduler can flexibly accommodate large numbers N_s of eNBs. However, the equal bandwidth assignments by the elementary equal share scheduler to the eNBs under-utilize the network resources when some eNBs have very little traffic while other eNBs have high traffic loads.

1.4.3 Traffic Adaptive Scheduling

With traffic adaptive scheduling, the Sm-GW collects uplink transmission requests from the eNBs. The Sm-GW then adaptively allocates portions of the uplink transmission bitrate G_{so} to the individual eNBs according to their requests. Traffic adaptive scheduling operates with a request-allocate-transmit cycle of duration W [seconds] illustrated in Fig. 1.6. At the start of the cycle, each eNB n, $n = 1, 2, \ldots, N_s$, sends an uplink transmission bitrate request to Sm-GW s. We let ρ_{son} denote the amount of traffic [in Byte] that eNB n wants to transmit to operator o over the next cycle of duration W. Once all requests have been received, i.e., following the principles of the offline scheduling framework [85], portions of G_{so} can be allocated to the eNBs according to some scheduling policy.

An elementary excess share scheduling policy [86] allocates the eNB grants as follows. Lightly loaded eNBs with $\rho_{son} < \Gamma_{so}$ are granted their full request, i.e., receive the grant size $\gamma_{son} = \rho_{son}$, while their unused (excess) portion of the equal share allocation is accumulated in an excess pool:

$$\xi = \sum_{\forall \rho_{son} \leq \Gamma_{so}} \Gamma_{so} - \rho_{son}. \tag{1.1}$$

Following the principles of controlled equitable excess allocation [86], highly loaded eNBs are allocated an equal share of the excess up to their request. That is, with $|\mathcal{H}|$ highly loaded eNBs, the grants are

$$\gamma_{son} = \min\left(\rho_{son},\ \Gamma_{so} + \frac{\xi}{|\mathcal{H}|}\right). \tag{1.2}$$

1.4.4 Scheduling Fairness

Within the context of our proposed Sm-GW scheduling framework, fairness is the measure of network accessibility of all N_s eNBs connected to an Sm-GW s based on individual eNB uplink throughput level requirements. We denote T_{son} for the long-run average throughput level [bit/s] of uplink traffic generated at eNB n, $n = 1, 2, \ldots, N_s$, at Sm-GW s for operator o. The throughput level T_{son} can for instance be obtained through smoothing of the requests ρ_{son} over successive cycles w. In order to avoid clutter, we omit the subscripts s and o in the remainder of this fairness evaluation. We define the following fair target throughput levels Ω_n [bit/s]: Lightly loaded eNBs $l \in \mathcal{L}$ with throughput levels $T_l < \Gamma/W$, should be able to transmit their full traffic load, i.e., $\Omega_l = T_l$. Next, consider highly loaded eNBs $h \in \mathcal{H}$ with throughput levels $T_h > \Gamma/W$. If the total throughput requirement of all eNBs $\sum_{l\in\mathcal{L}} T_l + \sum_{h\in\mathcal{H}} T_h$ is less than or equal to the uplink transmission bitrate G, then the highly loaded eNBs should be able to transmit their full traffic load, i.e., $\Omega_h = T_h$. On the other hand, if the total traffic load exceeds the uplink transmission bitrate, i.e., if $\sum_{l\in\mathcal{L}} T_l + \sum_{h\in\mathcal{H}} T_h > G$, then the highly loaded eNBs should be able to transmit traffic up to an equitable share of the uplink transmission bitrate not used by the lightly loaded eNBs. Thus, overall: $\Omega_h = \min\{T_h, \ (G - \sum\limits_{l\in\mathcal{L}} T_l)/|\mathcal{H}|\}$. We define the normalized distance $\mathcal{E}_n$ of the actually achieved (observed) throughput τ_n and the target throughput Ω_n, i.e., $\mathcal{E}_n = \tau_n - \Omega_n$.

Based on the preceding target throughput definitions, we obtain the normalized distance throughput fairness index [87]

$$\mathcal{F}_T = \frac{\sqrt{\sum_{n=1}^{N} \mathcal{E}_n^2}}{\sqrt{\sum_{n=1}^{N} \Omega_n^2}}, \qquad (1.3)$$

whereby $\mathcal{F}_T$ close to zero indicates fair Sm-GW scheduling.

1.4.5 Sm-GW Scheduling Overhead

In configuration adaptive Sm-GW scheduling, a reconfiguration event, i.e., an eNB connect or disconnect event, triggers the re-evaluation of the grant size limit Γ_{so}, see

Section 1.4.2. The new Γ_{so} value is sent to all eNBs. Since reconfiguration events occur typically only rarely, e.g., on the time scale of minutes or hours, the overhead for configuration adaptive scheduling is negligible.

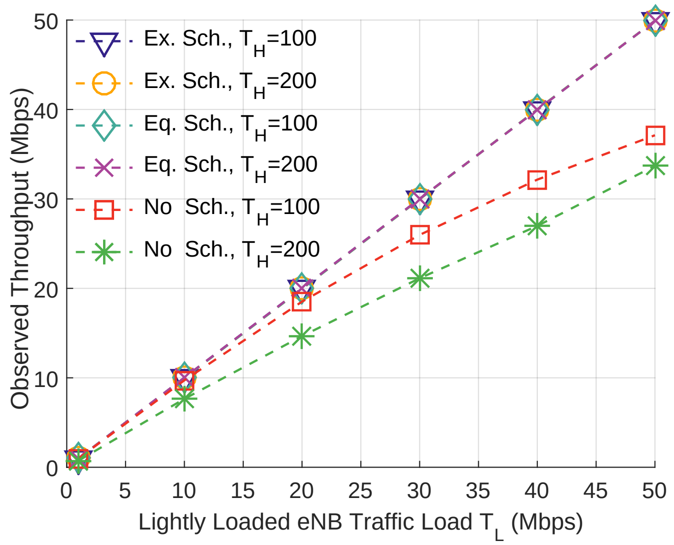
Traffic adaptive Sm-GW scheduling requires each eNB n to send a request every cycle of duration W seconds. Upon reception of the requests from all N_s eNBs, the Sm-GW evaluates and sends the grants to the respective eNBs, as illustrated in Fig. 1.6(a). The requests and grants can typically be sent simultaneously, i.e., in parallel, over the individual eNB-to-Sm-GW links. Thus, within a cycle duration W, the overhead amounts to the transmission delays of the request and grant messages, the maximum round-trip propagation delay between eNBs and Sm-GW, and the schedule processing delay at the Sm-GW. For typical parameter settings, such as 70 Byte messages transmitted at 1 Gbps, up to 500 m eNB-to-Sm-GW propagation distance, $W = 1$ ms cycle duration, and schedule processing delay on the order of microseconds, the overhead is less than half a percent.

1.4.6 Evaluation of Sm-GW Scheduling

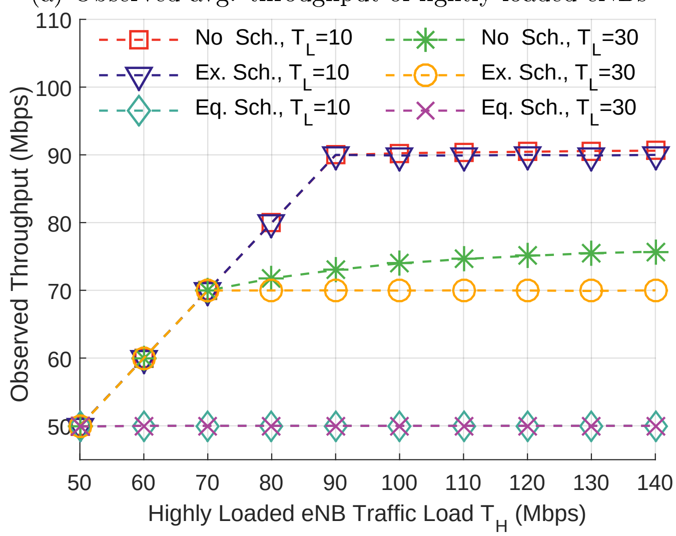
1.4.6.1 Simulation Setup

We evaluate the performance of Sm-GW scheduling with the discrete event simulator OMNET++. We consider a given Sm-GW s with an uplink transmission bitrate to a given operator o of $G_{so} = 1$ Gbps. We omit the subscripts s and o in the remainder of this evaluation section to avoid notational clutter. The LTE access network typically requires the packet delay to be less than 50 ms [88]. Therefore, we set the Sm-GW queue size to 20 MBytes, which is equivalent to a maximum queuing delay of 20 ms over the $G = 1$ Gbps link. Without any specific scheduling, the Sm-GW operates in first-come-first-served mode with taildrop.

We simulate the typical bursty eNB traffic generation pattern, with two eNB



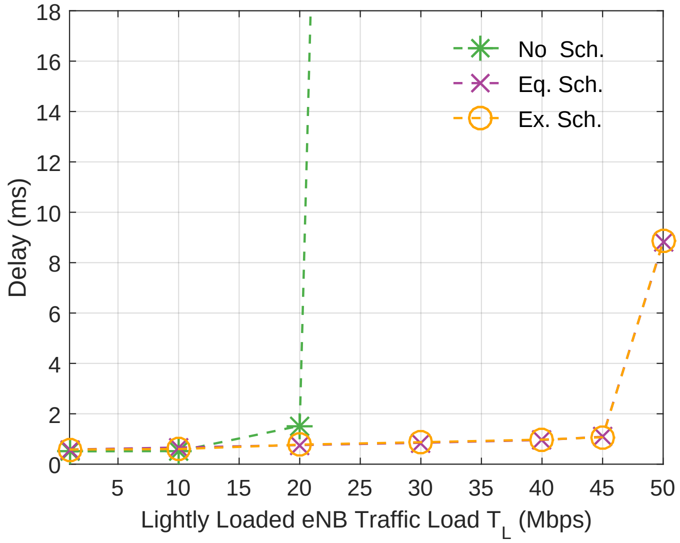
(a) Observed avg. throughput of lightly loaded eNBs



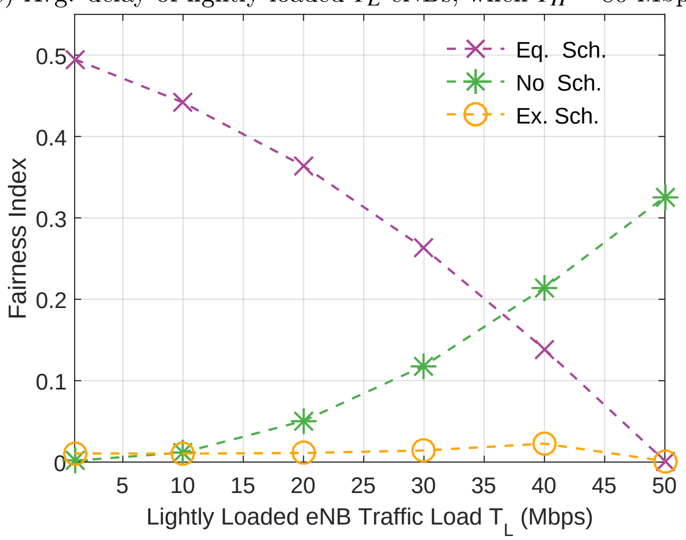
(b) Observed avg. throughput of highly loaded eNBs

traffic rate states: low and heavy. The sojourn time in a given traffic rate state is randomly drawn from a uniform distribution over 1 ms to 4 ms. At the end of the sojourn time, a switch to another state occurs with a probability of 70 % in the low traffic state and 30 % in the heavy traffic state. The traffic bitrate ratio between the heavy and low traffic states is 4 : 1. Within a given traffic rate state, data packets are randomly generated according to independent Poisson processes.

We consider $|\mathcal{L}| = 10$ lightly loaded eNBs and $|\mathcal{H}| = 10$ highly loaded eNBs



(c) Avg. delay of lightly loaded T_L eNBs, when $T_H = 80$ Mbps



(d) Fairness Index $\mathcal{F}_T$, when $T_H = 200$ Mbps.

Figure 1.7: Simulation results for Sm-GW scheduling.

connected to the considered Sm-GW. Each eNB, irrespective of whether it is lightly or highly loaded, generates traffic according to the two traffic rate state (low and heavy) model. The low and heavy traffic rates are set such that the long-run average generated traffic rate corresponds to a prescribed required throughput (load) level $T_L < G/N = 50$ Mbps for a lightly loaded eNB and a prescribed required throughput (load) level $T_H > G/N$ for a highly loaded eNB. For all simulations, the 95 %

confidence intervals are less than 5 % of the corresponding sample mean.

1.4.6.2 Simulation Results

Without Sm-GW Scheduling In Fig. 1.7, we show representative evaluation results comparing configuration adaptive equal-share Sm-GW scheduling and traffic adaptive excess-share Sm-GW scheduling with the conventional backhaul without Sm-GW scheduling. Figs. 1.7(a) and (b) show the actual (achieved, observed) throughput τ of lightly loaded and highly loaded eNBs, respectively, as a function of the generated lightly loaded (T_L) and highly loaded (T_H) throughput levels. We observe from Figs. 1.7(a) that without scheduling, the lightly loaded eNB suffer reductions in the achieved throughput, that are especially pronounced (over 30 %) for the high T_H = 200 Mbps load of the highly loaded eNBs. At the same time, we observe from Figure 1.7(b) that without scheduling, the highly loaded eNBs achieve more than their fair throughput share. For instance, for the highly loaded eNB throughput requirement (load) T_H = 140 Mbps, and T_L = 30 Mbps, the observed throughout of the highly loaded eNBs is τ_H = 76 Mbps, which is significantly higher than the fair share of $(G - |\mathcal{L}|T_L)/|\mathcal{H}|$ = 70 Mbps. The unfairness arising without scheduling is further illustrated in Fig. 1.7(c), where we observe a sharp delay increase at T_L = 20 Mbps, when the total traffic load $|\mathcal{L}|T_L + |\mathcal{H}|T_H$ approaches the uplink transmission bitrate G. Moreover, from Fig. 1.7(d), we observe an increasing fairness index $\mathcal{F}_T$ as the lightly loaded eNBs generate more traffic, i.e., as T_L increases. That is, as the lightly loaded eNBs try to transmit more traffic, their achieved throughput falls more and more below their fair share [see growing divergence between the no scheduling curves and straight lines for scheduling in Fig. 1.7(a)], leading to increasingly unfair treatment of the lightly loaded eNBs.

Equal-share Sm-GW Scheduling We observe from Fig. 1.7(a) and (c) that lightly loaded eNBs benefit from equal-share scheduling in that they get the full share of their fair target throughput and experience low delay. However, we observe from Fig. 1.7(b) that highly loaded eNBs achieve only a throughput of $G/(|\mathcal{L}| + |\mathcal{H}|) = 50$ Mbps as equal-share Sm-GW scheduling assigns a configuration adaptive allocation of equal shares of the limited uplink transmission bitrate G to all eNBs irrespective of their traffic generation rates. Correspondingly, we observe from Fig. 1.7(d), a high fairness index $\mathcal{F}_T$ for low traffic loads of the lightly loaded eNBs, as the highly loaded eNBs receive only unfairly small shares of the uplink transmission bitrate G.

Excess-share Sm-GW Scheduling We observe from Fig. 1.7(a) and (b) that with excess-share Sm-GW scheduling, both lightly loaded eNBs and highly loaded eNBs achieve their fair target throughput. We further observe from Figs. 1.7(c) and (d) that excess-share Sm-GW scheduling gives also favorable delay and fairness index performance.

Summary We conclude that scheduling of the Sm-GW uplink transmission bitrate G is necessary to prevent backhaul bandwidth starvation of lightly loaded eNBs due to the overwhelming traffic rates of highly loaded eNBs. On the other hand, simple configuration adaptive allocation of equal uplink transmission bitrate shares to each eNB wastes bandwidth. Flexible traffic adaptive scheduling according to the traffic loads of the eNBs, e.g., through excess-share scheduling, can ensure fairness while efficiently utilizing the uplink transmission bitrate.

1.5 SDN BASED MULTI-OPERATOR MANAGEMENT

1.5.1 Overview

In this section we introduce a novel SDN based network management framework for flexible sharing of the backhaul resources of multiple operators. In particular, the framework introduced in Sections 1.5.2–1.5.5 allows a set of Sm-GWs to flexibly share the uplink transmission bitrate of a given single operator. The inter-operator sharing introduced in Section 1.5.6 allows the Sm-GWs to flexibly share the uplink transmission bitrates of multiple operators. Our proposed multi-operator management framework accommodates dynamic changes of the traffic requirements of the small cells, such as changes of the generated uplink traffic bitrates, as well as dynamic changes of the operator characteristics, such as changes of the available uplink traffic bitrates. In the proposed multi-operator management framework, an SDN orchestrator dynamically configures the Sm-GWs and the transport network connecting the Sm-GWs to the operator gateways to flexibly adapt to changes in small cell traffic loads and the operator characteristics.

1.5.2 Request and Allocation Procedures

In a small cell deployment environment, such as a large organization, multiple Sm-GWs can serve multiple buildings. For example, in a university setting, a library can be equipped with an Sm-GW and the administration building can be equipped with another Sm-GW. The throughput requirements and priorities of these buildings typically vary widely over time. For instance, the administration building experiences a large visitor influx during graduation and student admission periods, while many students visit the library during exam week. Moreover, services from multiple operators may need to be shared among the buildings in a given organization, i.e., among multiple Sm-GWs. Hence, there is a need for highly flexible traffic management within the large organization based on time-varying priorities and throughput requirements.

Suppose, the Sm-GWs $s,\ s = 1, 2, \ldots, S$, and operators $o,\ o = 1, 2, \ldots, O$, are interconnected in a full mesh transport network, as illustrated in Fig. 1.8. As described in Section 1.4.3, with traffic adaptive Sm-GW scheduling, each eNB n sends

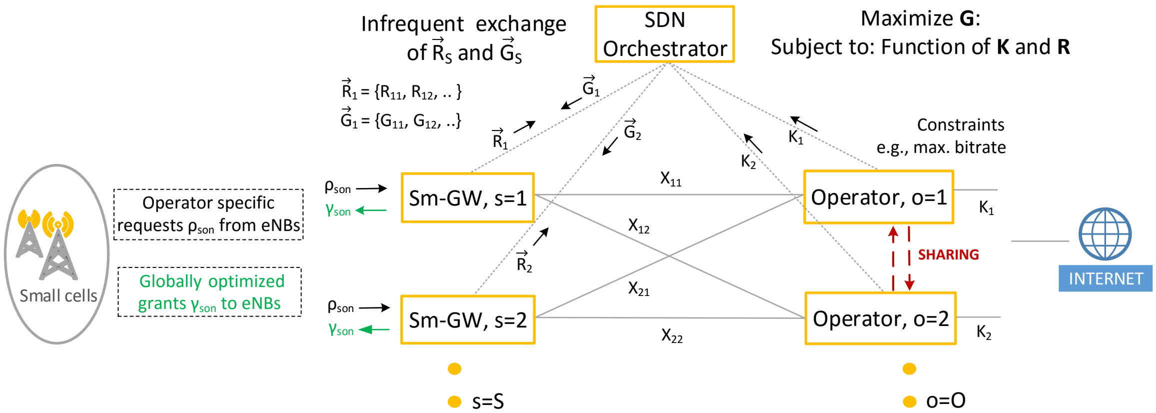


Figure 1.8: Illustration of SDN based multiple-operator management serving multiple Smart Gateways (Sm-GWs).

its operator o specific uplink transmission bitrate request to Sm-GW s in every cycle. The requested uplink transmission data amounts ρ_{son} will typically vary over time scales that are long enough to reasonably permit adaptations of the Sm-GW configurations. For instance, the requests will typically change on the time scales of several seconds or minutes, or possibly even longer, such as the seasonal variations in the visitor volume to university buildings. In order to obtain the variational characteristics of the eNB requirements, the operator specific requests at the Sm-GWs can be aggregated over the eNBs and appropriately smoothed, i.e., averaged over time, to obtain an aggregate smoothed uplink transmission bitrate request R_{so} [bit/s] from Sm-GW s to operator o.

Ideally, the backhaul network should adapt to varying requirements at the Sm-GWs to maximize the network utilization. We exploit the centralized control property of SDN to adaptively configure the network for variable requirements. More specifically, the SDN orchestrator in Fig. 1.8 optimizes the allocations G_{so} of operator o uplink transmission bitrate [bit/s] to the individual Sm-GWs s. The SDN orchestrator thus ensures that the grants to the eNBs are globally maximized (subject to the operators' constraints and requirements). When the optimized allocations G_{so} are used at the Sm-GW scheduler (Section 1.4), the maximum allowed traffic flow is sent from the Sm-GWs to each operator core.

1.5.3 Optimization Decision Variables and Constraints for Multi-Operator Management with Sm-GWs

In this section, we define a general optimization model for the multi-operator management framework. Specifically, we define the constraints and decision variables for optimizing the multi-operator management. The defined decision variables and constraints are employed for the operation of the SDN orchestrator, as detailed in Section 1.5.4. The SDN orchestrator can employ arbitrary objective functions and constraint allocation strategies for the optimization, as illustrated for an elementary example in Section 1.5.5.

1.5.3.1 Constraints

Requests for the uplink transmission of ρ_{son} [bits] from eNBs $n,\ n = 1, 2, \ldots, N_s$, arrive at Sm-GW $s,\ s = 1, 2, \ldots, S$, every cycle of duration W seconds, i.e., on the order of milliseconds, requesting uplink transmission bitrates from operator $o,\ o = 1, 2, \ldots, O$. The Sm-GW aggregates the requests over the eNBs n and smoothes the aggregated requests to obtain the smoothed aggregated requests R_{so}. Denoting w for the cycle index, an elementary weighted sampling smoothing computes

$$R_{so}(w) = \alpha \left(\frac{1}{N_s} \sum_{n=1}^{N_s} \frac{\rho_{son}(w)}{W} \right) + (1 - \alpha)\ R_{so}(w-1), \tag{1.4}$$

where α denotes the weight for the most recent request sample. A wide variety of other smoothing mechanism can be employed and optimized according to the specific deployment settings. The smoothed requests R_{so} are periodically (with a period typically much longer than the eNB reporting window) sent to the SDN orchestrator. In particular, each Sm-GW s, sends a vector of smoothed requests $\overrightarrow{R_s} = [R_{s1}\ R_{s2}\ \cdots\ R_{sO}]$ containing the aggregated and smoothed requests for each operator o to the SDN orchestrator. The SDN orchestrator combines the request vectors $\overrightarrow{R_s}$ to form the request matrix

$$\mathbf{R} = [R_{so}],\ \ s = 1, 2, \ldots, S;\ \ o = 1, 2, \ldots, O. \tag{1.5}$$

Each operator o, $o = 1, 2, \ldots, O$, can enforce a set of constraints K_{oc}, $c = 1, 2, \ldots, C$, represented by a constraint vector $\overrightarrow{K_o} = [K_{o1}\ K_{o2}\ \cdots\ K_{oC}]$ that is sent to the SDN orchestrator. Each constraint c may be associated with a particular specification from operator o, e.g., for traffic shaping of the flows or for the aggregate maximum bitrate. In order to avoid clutter and not to obscure the main ideas of our overall multi-operator management framework, we consider in this study a single constraint for each operator o. That is, in place of the constraint vector $\overrightarrow{K_o}$ we consider a single (scalar) constraint K_o. The SDN orchestrator combines the scalar constraints from the various operators o to form the constraint vector

$$\mathbf{K} = [K_1\ K_2\ \cdots\ K_O]. \tag{1.6}$$

1.5.3.2 Decision Variables

The Sm-GW s scheduler uses the operator o specific grant size limits Γ_{so} to schedule/assign uplink transmission grants to eNBs (see Sections 1.4.2 and 1.4.3). By controlling the variable Γ_{so} specific to operator o we can control the flow of traffic outward from the Sm-GW, i.e., towards the respective operator o. The long-term average traffic flow rates X_{so} [bit/s] from the Sm-GW s, $s = 1, 2, \ldots, S$, to the operators o, $o = 1, 2, \ldots, O$, can be expressed as matrix

$$\mathbf{X} = [X_{so}],\ \ s = 1, 2, \ldots, S; o = 1, 2, \ldots, O. \tag{1.7}$$

The operator o specific uplink transmission bitrates G_{so} granted to the Sm-GWs are evaluated at the SDN orchestrator, based on the request matrix $\mathbf{R}$ and the constraint vector $\mathbf{K}$. The orchestrator responds to the request vector $\overrightarrow{R_s}$ from each Sm-GW s with a grant vector $\overrightarrow{G_s}$. At the SDN orchestrator, the grant vectors $\overrightarrow{G_s}$ can be combined to form the orchestrator grant matrix

$$\mathbf{G} = [G_{so}], \ \ s = 1, 2, \ldots, S; o = 1, 2, \ldots, O. \tag{1.8}$$

$\mathbf{G}$ is a positive (non-negative) matrix, since the matrix elements G_{so}, $G_{so} \geq 0$, correspond granted uplink transmission bitrates.

Our objective is to maximize the traffic flow rates X_{so} from the Sm-GWs s to the operators o subject to the operator constraints $\mathbf{K}$. In particular, the aggregated traffic sent from the Sm-GWs s, $s = 1, 2, \ldots, S$, to the operator o core should satisfy the operator constraint K_o, i.e.,

$$\sum_{s=1}^{S} X_{so} \leq K_o, \quad \forall o, \ o = 1, 2, \ldots, O. \tag{1.9}$$

Using the grant vector $\overrightarrow{G_s}$ at Sm-GW s to assign, i.e., to schedule, uplink traffic grants to the eNBs (see Section 1.4) ensures that the traffic flow rates X_{so} from Sm-GW s to operator o are bounded by G_{so}, i.e.,

$$X_{so} \leq G_{so}, \quad \forall (s, o). \tag{1.10}$$

Thus, in order to ensure that the traffic flows X_{so} satisfy the operator constraints $\mathbf{K}$, the grants G_{so} must satisfy the operator constraints, i.e.,

$$\sum_{s=1}^{S} G_{so} \leq K_o, \qquad \forall o, \ o = 1, 2, \ldots, O. \tag{1.11}$$

In order to maximize the traffic flows X_{so} to each operator o, the SDN orchestrator needs to grant each Sm-GW s the maximum permissible uplink transmission bitrate G_{so}.

Algorithm 1: SDN Orchestrator procedure

1. Sm-GWs

(a) Evaluate aggregate smoothed requests R_{so} from eNB requests ρ_{son}, Eqn (1.4).

(b) Periodically send request vector $\overrightarrow{R_s}$ to SDN orchestrator

if *Grant vector* $\overrightarrow{G_s}$ *is received* **then**

  Update SM-GW (to eNBs) grant size limits Γ_{so},

end

2. Operators

(a) Send constraint K_o to SDN orchestrator

3. SDN Orchestrator

if *Request vector* $\overrightarrow{R_s}$ *is received* **OR** *constraint* K_o *is received* **then**

  Re-optimize orchestrator (to Sm-GW) grants $\mathbf{G}$;

  Send grant vector $\overrightarrow{G_s}$ to Sm-GW s;

end

1.5.4 SDN Orchestrator Operation

The operational procedures for evaluating the SDN orchestrator grant matrix $\mathbf{G}$ (1.8) are executed in parallel in the Sm-GWs, operators, and the SDN orchestrator, as summarized in Algorithm 1. The Sm-GWs aggregate and smooth the eNB requests and periodically send the request vector $\overrightarrow{R_s}$ to the SDN orchestrator. The SDN orchestrator optimizes the grant matrix $\mathbf{G}$ upon the arrival of a new Sm-GW request vector $\overrightarrow{R_s}$ or a change in an operator constraint K_o. The orchestrator updates the Sm-GWs with the newly evaluated orchestrator grant vectors $\overrightarrow{G_s}$, which update their grant size limits Γ_{so}.

Our SDN based multi-operator management framework allows for a wide variety of resource (uplink transmission bitrate) allocations from the multiple operators to the Sm-GWs. In order to illustrate the introduced framework, we consider next an elementary specific optimization problem formulation with a linear objective function and a proportional constraint allocation strategy that allocates the uplink transmission bitrate constraints proportional to the requests. More complex objective functions and allocation strategies, e.g., objective functions that prioritize specific grants are an interesting direction for future research. We note that this illustrative example does not exploit inter-operator sharing, which is examined in Section 1.5.6.

1.5.5 Illustrative Optimization Example with Linear Objective Function and Request-Proportional Constraint Allocations

Since the grants G_{so} are non-negative, an elementary objective function can linearly sum the grants G_{so}, i.e., as $\sum_{s=1}^{S}\sum_{o=1}^{O} G_{so}$. For the constraint allocation, we consider the aggregate over all Sm-GWs s of the aggregated smoothed requests R_{so} for a specific operator o, i.e., we consider the unit norm of the request vector $\|\overrightarrow{R_o}\|_1 = \sum_{s=1}^{S} R_{so}$. If $\|\overrightarrow{R_o}\|_1$ is less than the operator constraint K_o, then the corresponding grants G_{so} are set to the requests, i.e., $G_{so} = R_{so}$. On the other hand, if $\|\overrightarrow{R_o}\|_1 > K_o$, then we proportionally assign the operator o backhaul bandwidth K_o, i.e., we assign the proportion $R_{so}/\|\overrightarrow{R_o}\|_1$ of the constraint K_o. Thus,

$$G_{so} = \min\left(R_{so},\ \frac{R_{so}}{\|\overrightarrow{R_o}\|_1} K_o\right). \tag{1.12}$$

The resulting elementary optimization problem can be summarized as:

$$\begin{aligned}
&\text{Maximize} \quad \sum_{s=1}^{S}\sum_{o=1}^{O} G_{so} \\
&\text{Subject to:} \\
&\forall s \in \{1, 2, \ldots, S\} \quad \text{and} \quad \forall o \in \{1, 2, \ldots, O\}, \\
&-G_{so} \leq 0, \\
&G_{so} \leq R_{so}, \\
&G_{so} \leq K_o \frac{R_{so}}{\|\overrightarrow{R_o}\|_1}.
\end{aligned} \tag{1.13}$$

1.5.6 Inter-Operator Sharing

When the aggregate backhaul bandwidth $\|R_o\|_1$ requested from an operator o exceeds its constraint K_o, inter-operator sharing can be employed to route the additional traffic through the network managed by another operator. Our proposed Sm-GW multi-operator management provides a distinctive advantage in maintaining active connections with multiple operators to easily route the excess traffic to a sharing operator. We denote $o = m$ for the operator that accepts the sharing traffic from an other operator $o = e$ whose traffic constraint has been exceeded. In this study, we focus on one operator accepting sharing traffic and one operation with excess traffic. The extension to sets of multiple operators accepting sharing traffic and multiple operators with excess traffic is left for future research. An operator in sharing m should have low incoming traffic as compared to the constraints K_m in order to accept the traffic from the operator in excess e. Therefore, for the sharing ($o = m$) and excess ($o = e$) operators the requests R_{so} need to satisfy,

$$\sum_{s=1}^{S} R_{sm} < K_m, \quad \text{and} \quad \sum_{s=1}^{S} R_{se} > K_e. \tag{1.14}$$

The traffic rate from excess operator e that can be carried by sharing operator m depends on the unutilized slack uplink transmission bitrate of operator m:

$$\zeta = K_m - \sum_{s=1}^{S} R_{sm}. \tag{1.15}$$

If $\zeta > 0$, the last constraint in optimization problem (1.13) for the excess operator e is replaced by the constraint

$$G_{se} \leq (K_e + \zeta) \frac{R_{se}}{\|\overrightarrow{R_e}\|_1} \quad \forall s. \tag{1.16}$$

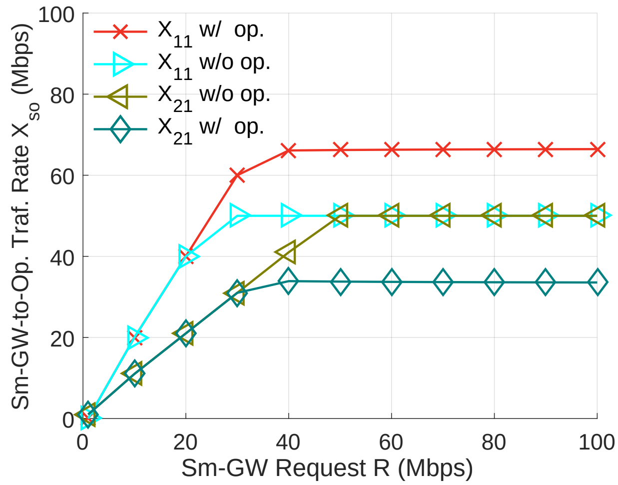


Figure 1.9: Traffic rates simulation.

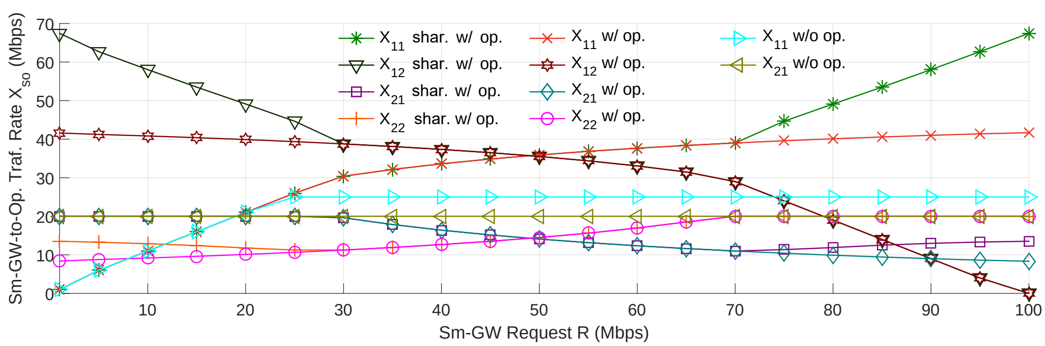


Figure 1.10: Inter-operator sharing evaluation.

1.5.7 Evaluation of Multi-Operator Management

In order to showcase the effectiveness of the SDN based multi-operator management framework, we conducted simulations for the elementary optimization with linear objective function and proportional constraint sharing (see Section 1.5.5). We consider $S = 2$ Sm-GWs and $O = 2$ operators. As comparison benchmark, we consider a static equal allocation of operator uplink transmission bitrate K_o to the S Sm-GWs, i.e., each Sm-GW s, $s = 1, 2$, is allocated K_o/S of the operator o uplink transmission bitrate.

1.5.7.1 Without Inter-Operator Sharing

In Fig. 1.9 we plot the Sm-GW s to operator o traffic flow rates X_{so} resulting from the optimized SDN orchestrator grants G_{so} as a function of the uplink transmission bitrate requested by Sm-GWs $s = 1$ and $s = 2$ from operator $o = 1$. Specifically, Sm-GW $s = 1$ requests bitrate $R_{11} = 2R$ and Sm-GW $s = 2$ requests bitrate $R_{21} = R$ from operator $o = 1$. The bitrate requests from operator $o = 2$ are fixed at 50 Mbps. Each operator o, $o = 1, 2$, has uplink transmission bitrate constraint $K_o = 100$ Mbps.

We observe from Fig. 1.9 that for requests for operator $o = 1$ bitrate up to $R = 25$ Mbps, the traffic rates X_{11} and X_{21} are equal to the requests, irrespective of whether SDN orchestrated optimization is employed for not. In contrast, as the requested bitrate increases above $R = 25$ Mbps, i.e., the bitrate $R_{11} = 2R$ requested by Sm-GW $s = 1$ from operator $o = 1$ increases above $K_1/S = 50$ Mbps, the granted bitrate G_{11} with SDN orchestration and the corresponding traffic flow X_{11} continue to increase. On the other hand, the granted bitrate G_{11} and traffic flow X_{11} without SDN orchestration stay limited at the static equal share $X_{11} = G_{11} = K_1/S = 50$ Mbps.

As the requested bitrate R increases above 33.3 Mbps, i.e., a total of $3R =$ 100 Mbps requested from operator $o = 1$, we observe from Fig. 1.9 that without orchestration, the traffic flow X_{21} from Sm-GW $s = 2$ to operator $o = 1$ grows to and then remains at the static equal share $K_1/S = 50$ Mbps. That is, the conventional static uplink transmission bitrate allocation results in unfair disproportional backhaul service. In contrast, our dynamic multi-operator management with SDN orchestrated optimization based on proportional sharing adaptively assigns the operator $o = 1$ bitrate to Sm-GWs $s = 1$ and $s = 2$ proportional to their requests.

1.5.7.2 With Inter-Operator Sharing

In Fig. 1.10, we plot the Sm-GW s to operator o traffic flow rates X_{so} as a function of the uplink transmission bitrate $R_{11} = R$ requested by Sm-GW $s = 1$ from operator $o = 1$ when inter-operator sharing is employed. Sm-GW $s = 1$ requests bitrate $R_{12} = 100 - R$ Mbps from operator $o = 2$. Also, Sm-GW $s = 2$ requests fixed bitrates $R_{21} = R_{22} = 20$ Mbps from each operator. Each operator o has a fixed uplink transmission bitrate constraint of $K_o = 50$ Mbps. Note that operator $o = (m) = 1$ has slack uplink transmission bitrate when $R \leq 30$ Mbps and can thus serve as roaming operator for the excess traffic to operator $e = 2$. As R increases and starts to exceed 70 Mbps, the roles are reversed, so that operator $e = 1$ can send some of its excess traffic to roaming operator $m = 2$.

Focusing initially on the case $R = 100$ Mbps, i.e., the right edge of Fig. 1.10, we observe that without SDN orchestrated optimization, Sm-GW $s = 1$ can only transmit at its fixed static allocation of $X_{11} = K_1/S = 25$ Mbps to operator $o = 1$, even though Sm-GW $s = 1$ has a traffic load demanding $R_{11} = R = 100$ Mbps. At the same time, Sm-GW $s = 2$ transmits at its requested rate $X_{21} = R_{21} = 20$ Mbps $< K_1/S$. Thus, the operator $o = 1$ uplink transmission bitrate K_1 is underutilized, even though Sm-GW $s = 1$ has more traffic to send, but cannot due to the inflexible static uplink transmission bitrate allocations.

With SDN orchestrated optimization with proportional sharing, the overloaded uplink transmission bitrate $K_1 = 50$ Mbps of operator $o = 1$ is shared between the two Sm-GWs, allowing Sm-GW $s = 1$ to transmit $X_{11} = R_{11}/(R_{11} + R_{21}) = 41.7$ Mbps, while Sm-GW $s = 2$ transmits $X_{21} = R_{21}/(R_{11} + R_{21}) = 8.3$ Mbps. However, the uplink transmission bitrate K_2 of operator $o = 2$ is underutilized with only Sm-GW $s = 2$

transmitting $X_{22} = 20$ Mbps.

With inter-operator sharing, the unutilized uplink transmission bitrate $\zeta = K_2 - X_{22} = 30$ Mbps of operator $o = 2$, is used to carry excess traffic from operator $o = 1$. In particular, the aggregate of the regular operator $o = 1$ uplink transmission bitrate K_1 and the uplink transmission bitrate available to operator $o = 1$ through traffic sharing to operator $o = 2$ ($\zeta = 30$ Mbps), i.e., $K_1 + \zeta = 80$ Mbps is available to operator $o = 1$. With proportional sharing, Sm-GW $s = 1$ can transmit $X_{11} = (K_1+\zeta)R_{11}/(R_{11}+R_{21}) = 66.7$ Mbps, while Sm-GW $s = 2$ can correspondingly transmit $X_{21} = 13.3$ Mbps, fully utilizing the backhaul capacities of both operators.

Overall, we observe from Fig. 1.10 that across the entire range of traffic loads R from Sm-GW $s = 1$ for operator $o = 1$, our SDN based multi-operator orchestration with sharing is able to fully utilize the uplink transmission bitrates of both operators. Note in particular, that depending on the traffic load, the roles of the two operators (excess or sharing) are dynamically adapted.

1.6 CONCLUSIONS

We have introduced a new backhaul architecture by inserting a novel Smart Gateway (Sm-GW) between the wireless base stations (eNBs) and the conventional operator gateways, e.g., LTE S/P-GWs. The Sm-GW enables flexible support for large numbers of small cell base stations. In particular, the Sm-GW adaptively schedules uplink backhaul transmission grants to the individual eNBs on a fast (typically millisecond) timescale. In addition, an SDN orchestrator adapts the allocation of the uplink transmission bitrate of the conventional gateways of multiple operators to the Sm-GWs on a slow (typically minutes or hours) time scale. Simulation results have demonstrated that the scheduling of eNB grants by the Sm-GW can greatly improve the backhaul service over conventional static backhaul uplink transmission bitrate allocations. Moreover, the SDN orchestrator substantially improves the utilization of the backhaul bandwidth, especially when inter-operator sharing is permitted.

There are several important directions for future research on the Sm-GW architecture and small cell backhaul in general. One direction is to examine a variety of scheduling algorithms in the context of the Sm-GW. Another direction is to examine different specific optimization objective functions within the general SDN orchestrator optimization introduced in this article. Moreover, it is of interest to investigate QoS strategies for different traffic types, such as data, voice, and video traffic [89–93].

CHAPTER 2

SOFTWARE DEFINED OPTICAL NETWORKS (SDONS): A COMPREHENSIVE SURVEY

2.1 INTRODUCTION

At least a decade ago [94] it was recognized that new network abstraction layers for network control functions needed to be developed to both simplify and automate network management. Software Defined Networking (SDN) [95–97] is the design principle that emerged to structure the development of those new abstraction layers. Fundamentally, SDN is defined by three architectural principles [98, 99]: (*i*) the separation of control plane functions and data plane functions, (*ii*) the logical centralization of control, and (*iii*) programmability of network functions. The first two architectural principles are related in that they combine to allow for network control functions to have a wider perspective on the network. The idea is that networks can be made easier to manage (i.e., control and monitor) with a move away from significantly distributed control. A tradeoff is then considered that balances ease of management arising from control centralization and scalability issues that naturally arise from that centralization.

The SDN abstraction layering consists of three generally accepted layers [98] inspired by computing systems, from the bottom layer to the top layer: (*i*) the *infrastructure* layer, (*ii*) the *control* layer, and (*iii*) the *application* layer, as illustrated in Fig. 2.1. The interface between the application layer and the control layer is referred to as the NorthBound Interface (NBI), while the interface between the control layer and the infrastructure layer is referred to as the SouthBound Interface (SBI). There are a variety of standards emerging for these interfaces, e.g., the OpenFlow protocol [100] for the SBI.

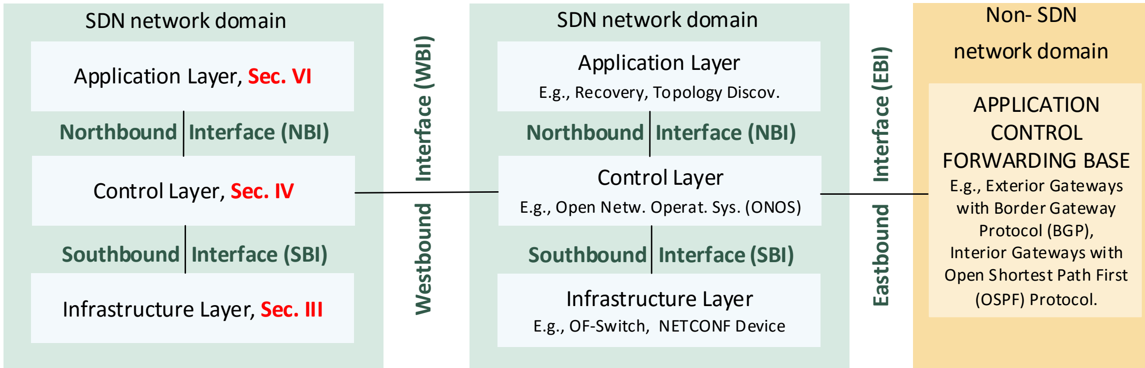


Figure 2.1: Illustration of Software Defined Networking (SDN) abstraction layers.

The *application* layer is modeled after software applications that utilize computing resources to complete tasks. The *control* layer is modeled after a computer's Operating System (OS) that manages computer resources (e.g., processors and memory), provides an abstraction layer to simplify interfacing with the computer's devices, and provides a common set of services that all applications can leverage. Device drivers in a computer's OS hide the details of interfacing with many different devices from the applications by offering a simple and unified interface for various device types. In the SDN model both the unified SBI as well as the control layer functionality provide the equivalent of a device driver for interfacing with devices in the *infrastructure* layer, e.g., packet switches.

Optical networks play an important role in our modern information technology due to their high transmission capacities. At the same time, the specific optical (photonic) transmission and switching characteristics, such as circuit, burst, and packet switching on wavelength channels, pose challenges for controlling optical networks. This article presents a comprehensive survey of Software Defined Optical Networks (SDONs). SDONs seek to leverage the flexibility of SDN control for supporting networking applications with an underlying optical network infrastructure. This survey comprehensively covers SDN related mechanisms that have been studied to date for optical networks.

2.1.1 Related Work

The general principles of SDN have been extensively covered in several surveys, see for instance, [95, 99–118]. SDN security has been surveyed in [119, 120], while management of SDN networks has been surveyed in [117] and SDN-based satellite networking is considered in [121].

To date, there have been relatively few overview and survey articles on SDONs. Zhang et al. [122] have presented a thorough survey on flexible optical networking based on Orthogonal Frequency Division Multiplexing (OFDM) in core (backbone) networks. The survey briefly notes how OFDM-based elastic networking can facilitate network virtualization and surveys a few studies on OFDM-based network virtualization in core networks.

Bhaumik et al. [123] have presented an overview of SDN and network virtualization concepts and outlined principles for extending SDN and network virtualization concepts to the field of optical networking. Their focus has been mainly on industry efforts, reviewing white papers on SDN strategies from leading networking companies, such as Cisco, Juniper, Hewlett-Packard, Alcatel-Lucent, and Huawei. A few selected academic research projects on general SDN optical networks, namely projects reported in the journal articles [7, 124] and a few related conference papers, have also been reviewed by Bhaumik et al. [123]. In contrast to Bhaumik et al. [123], we provide a comprehensive up-to-date review of academic research on SDONs. Whereas Bhaumik et al. [123] presented a small sampling of SDON research organized by research projects, we present a comprehensive SDON survey that is organized according to the SDN infrastructure, control, and application layer architecture.

For the SDON sub-domain of access networks, Cvijetic [125] has given an overview of access network challenges that can be addressed with SDN. These challenges include lack of support for on-demand modifications of traffic transmission policies and rules and limitations to vendor-proprietary policies, rules, and software. Cvijetic [125] also offers a very brief overview of research progress for SDN-based optical access networks, mainly focusing on studies on the physical (photonics) infrastructure layer. Cvijetic [126] has further expanded the overview of SDON challenges by considering the incorporation of 5G wireless systems. Cvijetic [126] has noted that SDN access networks are highly promising for low-latency and high-bandwidth back-hauling from 5G cell base stations and briefly surveyed the requirements and areas of future research required for integrating 5G with SDON access networks. A related overview of general software defined access networks based on a variety of physical transmission media, including copper Digital Subscriber Line (DSL) [127] and Passive Optical Networks (PONs), has been presented by Kerpez et al. [128].

Bitar [129] has surveyed use cases for SDN controlled broadband access, such as on-demand bandwidth boost, dynamic service re-provisioning, as well as value-add services and service protection. Bitar [129] has discussed the commercial perspective of the access networks that are enhanced with SDN to add cost-value to the network operation. Almeida Amazonas et al. [130] have surveyed the key issues of incorporating SDN in optical and wireless access networks. They briefly outlined the obstacles posed by the different specific physical characteristics of optical and wireless access networks.

Although our focus is on optical networks, for completeness we note that for the field of wireless and mobile networks, SDN based networking mechanisms have been surveyed in [131–137] while network virtualization has been surveyed in [138] for general wireless networks and in [139, 140] for wireless sensor networks. SDN and virtualization strategies for LTE wireless cellular networks have been surveyed in [141]. SDN-based 5G wireless network developments for mobile networks have been outlined in [142–145].

2.1.2 Survey Organization

We have mainly organize our survey according to the three-layer SDN architecture illustrated in Fig. 2.1. In particular, we have organized the survey in a bottom-up manner, surveying first SDON studies focused on the infrastructure layer in Section 2.3. Subsequently, we survey SDON studies focused on the control layer in Section 2.4. The virtualization of optical networks is commonly closely related to the SDN control layer. Therefore, we survey SDON studies focused on virtualization in Section 2.5, right after the SDON control layer section. Resuming the journey up the layers in Fig. 2.1, we survey SDON studies focused on the application layer in Section 2.6. We survey mechanisms for the overarching orchestration of the application layer and lower layers, possibly across multiple network domains (see Fig. 2.2), in Section 2.7. Finally, we outline open challenges and future research directions in Section 2.8 and conclude the survey in Section 2.9.

2.2 BACKGROUND

This section first provides background on Software Defined Networking (SDN), followed by background on virtualization and optical networking. SDN, as defined by the Internet Engineering Task Force (IETF) [146], is a networking paradigm enabling the programmability of networks. SDN abstracts and separates the data forwarding plane from the control plane, allowing faster technological development both in data and control planes. We provide background on the SDN architecture, including its architectural layers in Subsection 2.2.1. The network programmability provides the flexibility to dynamically initialize, control, manipulate, and manage the end-to-end network behavior via open interfaces, which are reviewed in Subsection 2.2.2. Subsequently, we provide background on network virtualization in Subsection 2.2.3 and on optical networking in Subsection 2.2.4.

2.2.1 Software Defined Networking (SDN) Architectural Layers

SDN offers a simplified view of the underlying network infrastructure for the network control and monitoring applications through the abstraction of each independent network layer. Fig. 2.1 illustrates the three-layer SDN architecture model consisting of application, control, and infrastructure layers as defined by the Open Networking Foundation (ONF) [98]. The ONF is the organization that is responsible for the publication of specifications for the OpenFlow protocol. The OpenFlow protocol [100, 147, 148] has been the first protocol for the SouthBound Interface (SBI, also referred to as Data-Controller Plane Interface (D-CPI)) between the control and infrastructure layers. Each layer operates independently, allowing multiple solutions to coexist within each layer, e.g., the infrastructure layer can be built from any programmable devices, which are commonly referred to as network elements [149] or network devices [146] (or sometimes as forwarding elements [150]). We will use the terminology network element throughout this survey. The SouthBound Interface (SBI) and the NorthBound Interface (NBI, also referred to as Application-Controller Plane Interface (A-CPI)) are defined as the primary interfaces interconnecting the SDN layers through abstractions. An SDN network architecture can coexist with both concurrent SDN architectures and non-SDN legacy network architectures. Additional interfaces are defined namely the EastBound Interface (EBI) and the WestBound Interface (WBI) [108] to interconnect the SDN architecture with external network architectures (the EBI and WBI are also collectively referred to as Intermediate-Controller Plane Interfaces (I-CPIs)). Generally, EBIs establish communication links to legacy network architectures (i.e., non-SDN networks); whereas, links to concurrent (side-by-side) SDN architectures are facilitated by the WBIs.

2.2.1.1 Infrastructure Layer

The infrastructure layer includes an environment for (payload) data traffic forwarding (data plane) either in virtual or actual hardware. The data plane comprises a network of network elements, which expose their capabilities through the SBI to the control plane. In traditional networking, control mechanisms are embedded within an infrastructure, i.e., decision making capabilities are embedded within the infrastructure to perform network actions, such as switching or routing. Additionally, these forwarding actions in the traditional network elements are autonomously established based on self-evaluated topology information that is often obtained through proprietary vendor-specific algorithms. Therefore, the configuration setups of traditional network elements are generally not reconfigurable without a service disruption, limiting the network flexibility. In contrast, SDN decouples the autonomous control functions, such as forwarding algorithms and neighbor discovery of the network nodes, and moves these control functions out of the infrastructure to a centrally controlled logical node, the controller. In doing so, the network elements act only as dumb switches which act upon the instructions of the controller. This decoupling reduces the network element complexity and improves reconfigurability.

In addition to decoupling the control and data planes, packet modification capabilities at the line-rates of network elements have been significantly improved with SDN. P4 [151] is a programmable protocol-independent packet processor, that can arbitrarily match the fields within any formatted packet and is capable of applying any arbitrary actions (as programmed) on the packet before forwarding. A similar forwarding mechanism, Protocol-oblivious Forwarding (PoF) has been proposed by Huawei Technologies [152].

2.2.1.2 Control Layer

The control layer is responsible for programming (configuring) the network elements (switches) via the SBIs. The SDN controller is a logical entity that identifies the south bound instructions to configure the network infrastructure based on application layer requirements. To efficiently manage the network, SDN controllers can request information from the SDN infrastructures, such as flow statistics, topology information, neighbor relations, and link status from the network elements (nodes). The software entity that implements the SDN controller is often referred to as *Network Operating System (NOS)*. Generally, a NOS can be implemented independently of SDN, i.e., without supporting SDN. On the other hand, in addition to supporting SDN operations, a NOS can provide advanced capabilities, such as virtualization, application scheduling, and database management. The Open Network Operating System (ONOS) [153] is an example of an SDN based NOS with a distributed control architecture designed to operate over Wide Area Networks (WANs). Furthermore, Cisco has recently developed the one Platform Kit (onePK) [154], which consists of a set of Application Program Interfaces (APIs) that allow the network applications to control Cisco network devices without a command line interface. The onePK libraries act as an SBI for Cisco ONE controllers and are based on C and Java compilers.

2.2.1.3 Application Layer

The application layer comprises network applications and services that utilize the control plane to realize network functions over the physical or virtual infrastructure. Examples of network applications include network topology discovery, provisioning, and fault restoration. The SDN controller presents an abstracted view of the network to the SDN applications to facilitate the realization of application functionalities. The applications can also include higher levels of network management, such as network

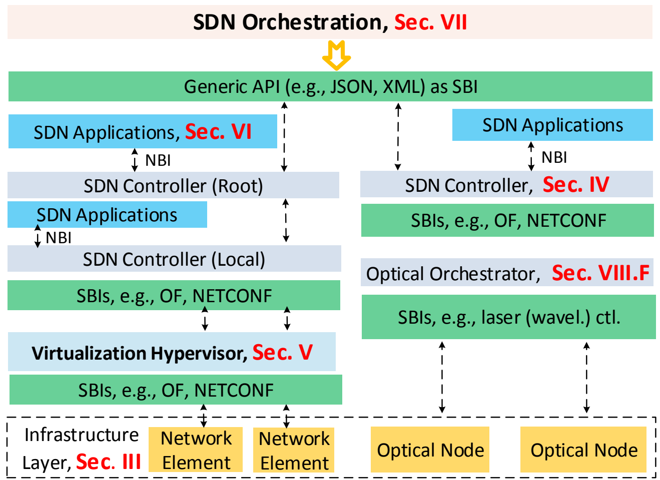


Figure 2.2: Overview of SDN orchestrator and SDN controllers.

data analytics, or specialized functions requiring processing in large data centers. For instance, the Central Office Re-architected as a Data center (CORD) [155] is an SDN application based on ONOS [153], that implements the typical central office network functions, such as optical line termination, as well as BaseBand Unit (BBU) and Data Over Cable Interface (DOCSIS) [156] processing as virtualized software entities, i.e., as SDN applications.

2.2.1.4 Orchestration Layer

Although the orchestration layer is commonly not considered one of the main SDN architectural layers illustrated in Fig. 2.1, as SDN systems become more complex, orchestration becomes increasingly important. We introduce therefore the orchestration layer as an important SDN architectural layer in this background section. Typically, an SDN orchestrator is the entity that coordinates software modules within a single SDN controller, a hierarchical structure of multiple SDN controllers, or a set of multiple SDN controllers in a “flat” arrangement (i.e., without a hierarchy) as illustrated in Fig. 2.2. An SDN controller in contrast can be viewed as a logically centralized single control entity. This logically centralized single control entity appears as the directly controlling entity to the network elements. The SDN controller is responsible for signaling the control actions or rules that are typically predefined (e.g., through OpenFlow) to the network elements. In contrast, the SDN orchestrator makes control decisions that are generally not predefined. More specifically, the SDN orchestrator could make an automated decision with the help of SDN applications or seek a manual recommendation from user inputs; therefore, results are generally not predefined. These orchestrator decisions (actions/configurations) are then delegated via the SDN controllers and the SBIs to the network elements.

Intuitively speaking, SDN orchestration can be viewed as a distinct abstracted (higher) layer for coordination and management that is positioned above the SDN control and application layers. Therefore, we generalize the term SDN orchestrator as an entity that realizes a wider, more general (more encompassing) network functionality as compared to the SDN controllers. For instance, a cloud SDN orchestrator can instantiate and tear down Virtual Machines (VMs) according to the cloud workload, i.e., make decisions that span across multiple network domains and layers. In contrast, SDN controllers realize more specific network functions, such as routing and path computation.

2.2.2 SDN Interfaces

2.2.2.1 Northbound Interfaces (NBIs)

A logical interface that interconnects the SDN controller and a software entity operating at the application layer is commonly referred to as a NorthBound Interface (NBI), or as Application-Controller Plane Interface (A-CPI).

REST REpresentational State Transfer (REST) [157] is generally defined as a software architectural style that supports flexibility, interoperability, and scalability. In the context of the SDN NBI, REST is commonly defined as an API that meets the

REST architectural style [158], i.e., is a so-called RESTful API:

- Client-Sever: Two software entities should follow the client-server model. In SDN, a controller can be a server and the application can be the client. This allows multiple heterogeneous SDN applications to coexist and operate over a common SDN controller.

- Stateless: The client is responsible for managing all the states and the server acts upon the client's request. In SDN, the applications collect and maintain the states of the network, while the controller follows the instructions from the applications.

- Caching: The client has to support the temporary local storage of information such that interactions between the client and server are reduced so as to improve performance and scalability.

- Uniform/Interface Contract: An overarching technical interface must be followed across all services using the REST API. For example, the same data format, such as Java Script Object Notation (JSON) or eXtended Markup Language (XML), has to be followed for all interactions sharing the common interface.

- Layered System: In a multilayered architectural solution, the interface should only be concerned with the next immediate node and not beyond. Thus, allowing more layers to be inserted, modified, or removed without affecting the rest of the system.

2.2.2.2 Southbound Interfaces (SBIs)

A logical interface that interconnects the SDN controller and the network element operating on the infrastructure layer (data plane) is commonly referred to as a South-

Bound Interface (SBI), or as the Data-Controller Plane Interface (D-CPI). Although a higher level connection, such as a UDP or TCP connection, is sufficient for enabling the communication between two entities of the SDN architecture, e.g., the controller and the network elements, specific SBI protocols have been proposed. These SBI protocols are typically not interoperable and thus are limited to work with SBI protocol-specific network elements (e.g., an OpenFlow switch does not work with the NETCONF protocol).

OpenFlow Protocol The interaction between an OpenFlow switching element (data plane) and an OpenFlow controller (control plane) is carried out through the OpenFlow protocol [100, 148]. This SBI (or D-CPI) is therefore also sometimes referred to as the OpenFlow control channel. SDN mainly operates through packet flows that are identified through matches on prescribed packet fields that are specified in the OpenFlow protocol specification. For matched packets, SDN switches then take prescribed actions, e.g., process the flow's packets in a particular way, such as dropping the packet, duplicating it on a different port or modifying the header information.

Path Computation Element Protocol (PCEP) The PCEP enables communication between the Path Computation Client (PCC) of the network elements and the Path Computation Element (PCE) residing within the controller. The PCE centrally computes the paths based on constraints received from the network elements. Computed paths are then forwarded to the individual network elements through the PCEP protocol [159, 160].

Network Configuration Protocol (NETCONF) Protocol The NETCONF protocol [161] provides mechanisms to configure, modify, and delete configurations on a network device. Configuration of the data and protocol messages are encoded in the NETCONF protocol using an eXtensible Markup Language (XML). Remote procedure calls are used to realize the NETCONF protocol operations. Therefore, only devices that are enabled with required remote procedure calls allow the NETCONF protocol to remotely modify device configurations.

Border Gateway Protocol Link State Distribution (BGP-LS) Protocol The central controller needs a topology information database, also known as Traffic Engineering Database (TED), for optimized end-to-end path computation. The controller has to request the information for building the TED, such as topology and bandwidth utilization, via the SBIs from the network elements. This information can be gathered by a BGP extension, which is referred to as BGP-LS.

2.2.3 Network Virtualization

Analogously to the virtualization of computing resources [162, 163], network virtualization abstracts the underlying physical network infrastructure so that one or multiple virtual networks can operate on a given physical network [164–172]. Virtual networks can span over a single or multiple physical infrastructures (e.g., geographically separated WAN segments). Network Virtualization (NV) can flexibly create independent virtual networks (slices) for distinct users over a given physical infrastructure. Each network slice can be created with prescribed resource allocations. When no longer required, a slice can be deleted, freeing up the reserved physical resources.

Network hypervisors [173, 174] are the network elements that abstract the physical network infrastructure (including network elements, communication links, and control functions) into logically isolated virtual network slices. In particular, in the case of an underlying physical SDN network, an SDN hypervisor can create multiple isolated virtual SDN networks [79, 175]. Through hypervisors, NV supports the implementation of a wide range of network services belonging to the link and network protocol layers (L2 and L3), such as switching and routing. Additionally, virtualized infrastructures can also support higher layer services, such as load-balancing of servers and firewalls. The implementation of such higher layer services in a virtualized environment is commonly referred to as Network Function Virtualization (NFV) [176–180]. NFV can be viewed as a special case of NV in which network functions, such as address translation and intrusion detection functions, are implemented in a virtualized environment. That is, the virtualized functions are implemented in the form of software entities (modules) running on a data center (DC) or the cloud [181]. In contrast, the term NV emphasizes the virtualization of the network resources, such as communication links and network nodes.

2.2.4 Optical Networking Background

2.2.4.1 Optical Switching Paradigms

Optical networks are networks that either maintain signals in the optical domain or at least utilize transmission channels that carry signals in the optical domain. In optical networks that maintain signals in the optical domain, switching can be performed at the *circuit, packet, or burst* granularities.

Circuit Switching Optical *circuit* switching can be performed in space, waveband, wavelength, or time. The optical spectrum is divided into wavelengths either on a fixed wavelength grid or on a flexible wavelength grid. Spectrally adjacent wavelengths can be coalesced into wavebands. The fixed wavelength grid standard (ITU-T G.694.1) specifies specific center frequencies that are either 12.5 GHz, 25 GHz, 50 GHz, or 100 GHz apart. The flexible DWDM grid (flexi-grid) standard (ITU-T G.694.1) [122, 182–184] allows the center frequency to be any multiple of 6.25 GHz away from 193.1 THz and the spectral width to be any multiple of 12.5 GHz. Elastic

Optical Networks (EONs) [185–187] that take advantage of the flexible grid can make more efficient use of the optical spectrum but can cause spectral fragmentation, as lightpaths are set up and torn down, the spectral fragmentation counteracts the more efficient spectrum utilization [188].

Packet Switching Optical *packet* switching performs packet-by-packet switching using header fields in the optical domain as much as possible. An all-optical packet switch requires [189]:

- Optical synchronization, demultiplexing, and multiplexing
- Optical packet forwarding table computation
- Optical packet forwarding table lookup
- Optical switch fabric
- Optical buffering

Optical packet switches typically relegate some of these design elements to the electrical domain. Most commonly the packet forwarding table computation and lookup is performed electrically. When there is contention for a destination port, a packet needs to be buffered optically, this buffering can be accomplished with rather impractical fiber delay lines. Fiber delay lines are fiber optic cables whose lengths are configured to provide a certain time delay of the optical signal; e.g., 100 meters of fiber provides 500 ns of delay. An alternative to buffering is to either drop the packet or to use deflection routing, whereby a packet is routed to a different output that may or may not lead to the desired destination.

Burst Switching Optical *burst* switching alleviates the requirements of optical packet forwarding table computation, forwarding table lookup, as well as buffering while accommodating bursty traffic that would lead to poor utilization of optical circuits. In essence, it permits the rapid establishment of short-lived optical circuits to support the transfer of one or more packets coalesced into a burst. A control packet is sent through the network that establishes the lightpath for the burst and then the burst is transmitted on the short-lived circuit with no packet lookup or buffering required along the path [189]. Since the circuit is only established for the length of the burst, network resources are not wasted during idle periods. To avoid any buffering of the burst in the optical network, the burst transmission can begin once the lightpath establishment has been confirmed (tell-and-wait) or a short time period after the control packet is sent (just-enough-time). *Note*: Sending the burst immediately after the control packet (tell-and-go) would require some buffering of the optical burst at the switching nodes.

2.2.4.2 Optical Network Structure

Optical networks are typically structured into three main tiers, namely access networks, metropolitan (metro) area networks, and backbone (core) networks [190].

Access Networks In the area of optical access networks [191], so-called Passive Optical Networks (PONs), in particular, Ethernet PONs (EPONs) and Gigabit PONs (GPONs) [192, 193], have been widely studied. A PON has typically an inverse tree structure with a central Optical Line Terminal (OLT) connecting multiple distributed Optical Network Units (ONUs; also referred to as Optical Network Terminals, ONTs) to metro networks. In the downstream (OLT to ONUs) direction, the OLT broadcasts transmissions. However, in the upstream (ONUs to OLT) direction, the transmissions of the distributed ONUs need to be coordinated to avoid collisions on the shared upstream wavelength channel. Typically, a cyclic polling based Medium Access Control (MAC) protocol, e.g., based on the MultiPoint Control Protocol (MPCP, IEEE 802.3ah), is employed. The ONUs report their bandwidth demands to the OLT and the OLT then assigns upstream transmission windows according to a Dynamic Bandwidth Allocation (DBA) algorithm [85, 194–196]. Conventional PONs cover distances up to 20 km, while so-called Long-Reach (LR) PONs cover distances up to around 100 km [197–199].

Recently, hybrid access networks that combine multiple transmission media, such as Fiber-Wireless (FiWi) networks [200–204] and PON-DSL networks [205], have been explored to take advantage of the respective strengths of the different transmission media.

Networks Connected to Access Networks Optical access networks provide Internet connectivity for a wide range of peripheral networks. Residential (home) wired or wireless local area networks [206] typically interconnect individual end devices (hosts) in a home or small business and may connect directly with an optical access network. Cellular wireless networks provide Internet access to a wide range of mobile devices [207–209]. Specialized cellular backhaul networks [210–216] relay the traffic to/from base stations of wireless cellular networks to either wireless access networks [217–222] or optical access networks. Moreover, optical access networks are often employed to connect Data Center (DC) networks to the Internet. DC networks interconnect highly specialized server units that process and store large data amounts with specialized networking technologies [223–227]. Data centers are typically employed to provide the so-called “cloud” services for commercial and social media applications.

SDN Controlled Photonic Communication Infrastructure Layer, Sec. 2.3

Bandwidth Variable Transceivers (BVTs), Sec. 2.3.1
- Single-Flow BVTs [234–236], Sec. 2.3.1.1
  - Mach-Zehnder Modulator Based [237, 238]
  - BVTs for PONs [1, 239–244]
  - BVTs for DC Netw. [245]
- Sliceable Multi-Flow BVTs [246], Sec. 2.3.1.2
  - Encoder Based [247–249]
  - DSP Based [250]
  - Subcar. + Mod. Pool Based [2]
  - HYDRA [251]

Space Div. Multipl. (SDM)-SDN, Sec. 2.3.2 [252–254]

Switching, Sec. 2.3.3
- Switching Elements, Sec. 2.3.3.1
  - ROADMs [255–260]
  - Open Transport Switch (OTS) [261]
  - Logical xBar [262]
  - Optical White Box [263]
  - GPON Virt. Sw. [264–268]
  - Flexi Access Netw. Node [269, 270]
- Switching Paradigm, Sec. 2.3.3.2
  - Converged Pkt-Cir. Sw. [271–277]
  - R-LR-UFAN [278–280]
  - Flexi-grid [281–284]

Opt. Perf. Monitoring, Sec. 2.3.4
- Cognitive Netw. Infra. [285–287]
- Wavelength Selective Switch/Amplifier Control [288–291]

Figure 2.3: Classification of physical infrastructure layer SDON studies.

Metropolitan Area Networks Optical Metropolitan (metro) Area Networks (MANs) interconnect the optical access networks in a metropolitan area with each other and with wide-area (backbone, core) networks. MANs have typically a ring or star topology [228–233] and commonly employ optical networking technologies.

Backbone Networks Optical backbone (wide area) networks interconnect the individual MANs on a national or international scale. Backbone networks have typically a mesh structure and employ very high speed optical transmission links.

2.3 SDN CONTROLLED PHOTONIC COMMUNICATION INFRASTRUCTURE LAYER

This section surveys mechanisms for controlling physical layer aspects of the optical (photonic) communication infrastructure through SDN. Enabling the SDN control down to the photonic level operation of optical communications allows for flexible adaptation of the photonic components supporting optical networking functionalities [124, 292–294]. As illustrated in Fig. 2.3, this section first surveys transmitters and receivers (collectively referred to as transceivers or transponders) that permit SDN control of the optical signal transmission characteristics, such as modulation format. We also survey SDN controlled space division multiplexing (SDM), which provides an emerging avenue for highly efficient optical transmissions. Then, we survey SDN controlled optical switching, covering first switching elements and then overall switching paradigms, such as converged packet and circuit switching. Finally, we survey cognitive photonic communication infrastructures that monitor the optical signal quality. The optical signal quality information can be used to dynamically control the transceivers as well as the filters in switching elements.

2.3.1 Transceivers

Software defined optical transceivers are optical transmitters and receivers that can be flexibly configured by SDN to transmit or receive a wide range of optical signals [295]. Generally, software defined optical transceivers vary the modulation format [296] of the transmitted optical signal by adjusting the transmitter and receiver operation through Digital Signal Processing (DSP) techniques [297–299]. These transceivers have evolved in recent years from Bandwidth Variable Transceivers (BVTs) generating a single signal flow to sliceable multi-flow BVTs. Single-flow BVTs permit SDN control to adjust the transmission bandwidth of the single generated signal flow. In contrast, sliceable multi-flow BVTs allow for the independent SDN control of multiple communication traffic flows generated by a single BVT.

2.3.1.1 Single-Flow Bandwidth Variable Transceivers (BVTs)

Software defined optical transceivers have initially been examined in the context of adjusting a single optical signal flow for flexible WDM networking [234–236]. The goal has been to make the photonic transmission characteristics of a given transmitter fully programmable. We proceed to review a representative single-flow BVT design for general optical mesh networks in detail and then summarize related single-flow BVTs for PONs and data center networks.

Mach-Zehnder Modulator Based Flexible Transmitter Choi and Liu et al. [237, 238] have demonstrated a flexible transmitter based on Mach-Zehnder Modulators (MZMs) [300] and a corresponding flexible receiver for SDN control in a general mesh network. The flexible transceiver employs a single dual-drive MZM that is fed by two binary electric signals as well as a parallel arrangement of two MZMs which are fed by two additional electrical signals. Through adjusting the direct current bias voltages and amplitudes of drive signals the combination of MZMs can vary the amplitude and phase of the generated optical signal [301]. Thus, modulation formats ranging from Binary Phase Shift Keying (BPSK) to Quadrature Phase Shift Keying (QPSK) as well as 8 and 16 quadrature amplitude modulation [296] can be generated. The amplitudes and bias voltages of the drive signals can be signaled through an SDN OpenFlow control plane to achieve the different modulation formats. The corresponding flexible receiver consists of a polarization filter that feeds four parallel photodetectors, each followed by an Analog-to-Digital Converter (ADC). The outputs of the four parallel ADCs are then processed with DSP techniques to automatically (without SDN control) detect the modulation format. Experiments in [237, 238] have evaluated the bit error rates and transmission capacities of the different modulation formats and have demonstrated the SDN control.

Single-Flow BVTs for PONs Flexible optical networking with real-time bandwidth adjustments is also highly desirable for PON access and metro networks, albeit the BVT technologies for access and metro networks should have low cost and complexity [239]. Iiyama et al. [240] have developed a DSP based approach that employs SDN to coordinate the downstream PON transmission of On-Off Keying (OOK) modulation [241] and Quadrature Amplitude Modulation (QAM) [242] signals. The OOK-QAM-SDN scheme involves a novel multiplexing method, wherein all the data are simultaneously sent from the OLT to the ONUs and the ONUs filter the data they need. The experimental setup in [240] also demonstrated digital software ONUs that concurrently transmit data by exploiting the coexistence of OOK and QAM. The OOK-QAM-SDN evaluations demonstrated the control of the receiving sensitivity which is very useful for a wide range of transmission environments.

In a related study, Vacondio et al. [243] have examined Software-Defined Coherent Transponders (SDCT) for TDMA PON access networks. The proposed SDCT digitally processes the burst transmissions to achieve improved burst mode transmissions according to the distance of a user from the OLT. The performance results indicate that the proposed flexible approach more than doubles the average transmission capacity per user compared to a static approach.

Bolea et al. [1, 244] have recently developed low-complexity DSP reconfigurable ONU and OLT designs for SDN-controlled PON communication. The proposed communication is based on carrierless amplitude and phase modulation [302] enhanced with optical Orthogonal frequency Division Multiplexing (OFDM) [244]. The different OFDM channels are manipulated through DSP filtering. As illustrated in Fig. 2.4, the ONU consists of a DSP controller that controls the filter coefficients of the shap-

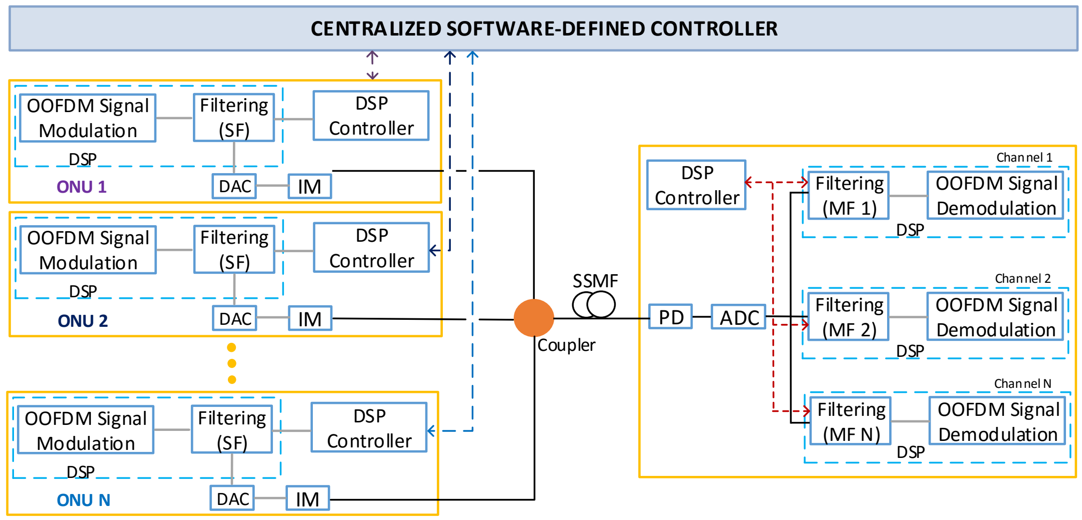


Figure 2.4: Illustration of DSP reconfigurable ONU and OLT designs [1].

ing filter. The filter output is then passed through a Digital-to-Analog Converter (DAC) and intensity modulator for electric-optical conversion. At the OLT, a photo diode converts the optical signal to an electrical signal, which then passes through an Analog-to-Digital Converter (ADC). The SDN controlled OLT DSP controller sets the filter coefficients in the matching filter to correspond to the filtering in the sending ONU. The OLT DSP controller is also responsible for ensuring the orthogonality of all the ONU filters in the PON. The performance evaluations in [1] indicate that the proposed DSP reconfigurable ONU and OLT system achieves ONU signal bitrates around 3.7 Gb/s for eight ONUs transmitting upstream over a 25 km PON. The performance evaluations also illustrate that long DSP filter lengths, which increase the filter complexity, improve performance.

Single-Flow BVTs for Data Center Networks Malacarne et al. [245] have developed a low-complexity and low-cost bandwidth adaptable transmitter for data center networking. The transmitter can multiplex Amplitude Shift Keying (ASK), specifically

On-Off Keying (OOK), and Phase Shift Keying (PSK) on the same optical carrier signal without any special synchronization or temporal alignment mechanism. In particular, the transmitter design [245] uses the OOK electronic signal to drive a Mach-Zehnder Modulator (MZM) that is fed by the optical pulse modulated signal. SDN control can activate (or de-activate) the OOK signal stream, i.e., adapt from transmitting only the PSK signal to transmitting both the PSK and OOK signal and thus providing a higher transmission bit rate.

2.3.1.2 Sliceable Multi-Flow Bandwidth Variable Transceivers

Whereas the single-flow transceivers surveyed in Section 2.3.1.1 generate a single optical signal flow, parallelization efforts have resulted in multi-flow transceivers (transponders) [246]. Multi-flow transceivers can generate multiple parallel optical signal flows and thus form the infrastructure basis for network virtualization.

Encoder Based Programmable Transponder Sambo et al. [247, 248] have developed an SDN-programmable bandwidth-variable multi-flow transmitter and corresponding SDN-programmable multi-flow bandwidth variable receiver, referred to jointly as programmable bandwidth-variable transponder. The transmitter mainly consists of a programmable encoder and multiple parallel Polarization-Multiplexing Quadrature Phase Shift Keying (PM-QPSK [296]) laser transmitters, whose signals are multiplexed by a coupler. The encoder is SDN-controlled to implement Low-Density Parity-Check (LDPC) coding [303] with different code rates. At the receiver, the SDN control sets the local oscillators and LDPC decoder. The developed transponder allows the setting of the number of subcarriers, the subcarrier bitrate, and the LDPC coding rate through SDN. Related frequency conversion and defragmentation issues have been examined in [304]. In [249], a low-cost version of the SDN programmable transponder with a multiwavelength source has been developed. The multiwavelength

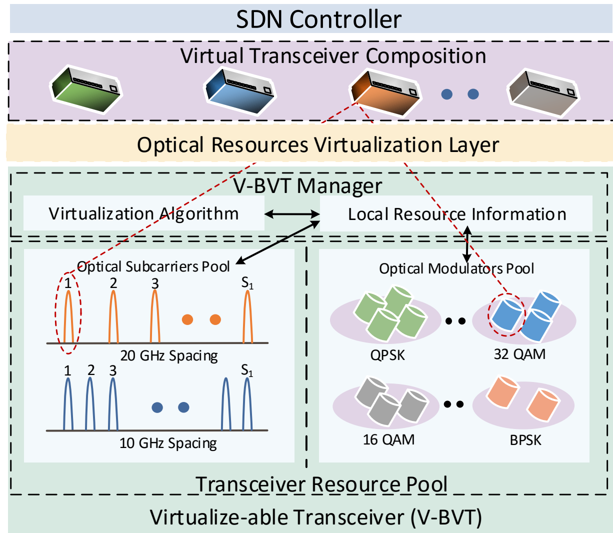


Figure 2.5: Illustration of Subcarrier and Modulator Pool Based Virtualizable Bandwidth Variable Transceiver (V-BVT) [2].

source is based on a micro-ring resonator [305] that generates multiple signal carriers with only a single laser. Automated configuration procedures for the comprehensive set of transmission parameters, including modulation format, coding configuration, and carriers have been explored in [306].

DSP Based Sliceable BVT Moreolo et al. [250] have developed an SDN controlled sliceable BVT based on adaptive Digital Signal Processing (DSP) of multiple parallel signal subcarriers. Each subcarrier is fed by a DSP module that configures the modulation format, including the bit rate setting, and the power level of the carrier by adapting a gain coefficient. The output of the DSP module is then passed through digital to analog conversion that drives laser sources. The parallel flows can be combined with a wavelength selective switch; the combined flow can be sliced into multiple distinct sub-flows for distinct destinations. The functionality of the developed DSP based BVT has been verified for a metropolitan area network with links reaching up to 150 km.

Subcarrier and Modulator Pool Based Virtualizable BVT Ou et al. [2, 307] have developed a Virtualizable BVT (V-BVT) based on a combination of an optical subcarriers pool with an independent optical modulators pool, as illustrated in Fig. 2.5. The emphasis of the design is on implementing Virtual Optical Networks (VONs) at the transceiver level. The optical subcarriers pool contains multiple optical carriers, whereby channel spacing and central frequency (wavelength channel) can be selected. The optical modulators pool contains optical modulators that can generate a wide variety of modulation formats. The SDN control interacts with a V-BVT Manager that implements a virtualization algorithm. The virtualization algorithm generates a transceiver slice by combining a particular set of subcarriers (with specific number of subcarriers, channel spacing, and central frequencies) from the optical subcarriers pool with a particular modulation (with specific number of modulators and modulation formats) from the optical modulators pool. The evaluations in [2] have evaluated the proposed V-BVT in a network testbed with path lengths up to 200 km with 20 GHz channel spacing and a variety of modulation formats, including BPSK as well as 16QAM and 32QAM.

S-BVT Based Hybrid Long-Reach Fiber Access Network (HYDRA) HYDRA [251] is a novel hybrid long-reach fiber access network architecture based on sliceable BVTs. HYDRA supports low-cost end-user ONUs through an Active Remote Node (ARN) that directly connects via a distribution fiber segment, a passive remote node, and a trunk fiber segment to the core (backbone) network, bypassing the conventional metro network. The ARN is based on an SDN controlled S-BVT to optimize the modulation format. With the modulation format optimization, the ARN can optimize the transmission capacity for the given distance (via the distribution and trunk fiber segments) to the core network. The evaluations in [251] demonstrate good bit error rate performance of representative HYDRA scenarios with a 200 km trunk fiber segment and distribution fiber lengths up to 100 km. In particular, distribution fiber lengths up to around 70 km can be supported without Forward Error Correction (FEC), whereas distribution fiber lengths above 70 km would require standard FEC. The consolidation of the access and metro network infrastructure [308] achieved through the optimized S-BVT transmissions can significantly reduce the network cost and power consumption.

2.3.2 Space Division Multiplexing (SDM)-SDN

Amaya et al. [252, 253] have demonstrated SDN control of Space Division Multiplexing (SDM) [309] in optical networks. More specifically, Amaya et al. employ SDN to control the physical layer so as to achieve a bandwidth-flexible and programmable SDM optical network. The SDN control can perform network slicing, resulting in sliceable superchannels. A superchannel consists of multiple spatial carriers to support dynamic bandwidth and QoS provisioning.

Galve et al. [254] have built on the flexible SDN controlled SDM communication principles to develop a reconfigurable Radio Access Network (RAN). The RAN connects the BaseBand processing Units (BBUs) in a shared central office with the corresponding distributed Remote Radio Heads (RRHs) located at Base Stations (BSs). A multicore fiber operated with SDM [309] connects the RRHs to the BBUs in the central office. Galve et al. introduce a radio over fiber operation mode where SDN controlled switching maps the subcarriers dynamically to spatial output ports. A complementary digitized radio over fiber operating mode maintains a BBU pool. Virtual BBUs are dynamically allocated to the cores of the SDM operated multicore fiber.

2.3.3 SDN-Controlled Switching

2.3.3.1 Switching Elements

ROADM The Reconfigurable Optical Add-Drop Multiplexer (ROADM) is an important photonic switching device for optical networks. Through wavelength selective optical switches, a ROADM can drop (or add) one or multiple wavelength channels carrying optical data signals from (to) a fiber without requiring the conversion of the optical signal to electric signals [310]. The ROADM thus provides an elementary switching functionality in the optical wavelength domain. Initial ROADM based node architectures for cost-effectively supporting flexible SDN networks have been presented in [255]. Conventional ROADM networks have typically statically configured wavelength channels that transport traffic along a pre-configured route. Changes of wavelength channels or routes in the statically configured networks incur presently high operational costs due to required physical interventions and are therefore typically avoided. New ROADM node designs allow changes of wavelength channels and routes through a management control plane. Due to these two flexibility dimensions (wavelength and route), these new ROADM nodes are referred to as "colorless" and "directionless". First designs for such colorless and directionless ROADM nodes have been outlined in [255] and further elaborated in [256, 257]. In addition to the colorless and directionless properties, the contentionless property has emerged for ROADMs [236]. Contentionless ROADM operation means that any port can be routed on any wavelength (color) in any direction without causing resource contention. Designs for such Colorless-Directionless-Contentionless (CDC) ROADMs have been proposed in [258, 259]. In general, the ROADM designs consist of an express bank that interconnects the input and output ports coming from/leading to other ROADMs, and an add-drop bank that connects the express bank with the local receivers for dropped wavelength channels or transmitters for added wavelength channels. The recent designs have focused on the add-drop bank and explored different arrangements of wavelength selective switches and multicast switches to provide add-drop bank functionality with the CDC property [258, 259].

Garrich et al. [260] have recently designed and demonstrated a CDC ROADM with an add-drop bank based on an Optical Cross-Connect (OXC) backplane [311]. The OXC backplane allows for highly flexible add/drop configurations implemented through SDN control. The backplane based ROADM has been analytically compared with prior designs based on wavelength selective and multicast switches and has been shown to achieve higher flexibility and lower losses. An experimental evaluation has tested the backplane based ROADM for a metropolitan area mesh network extending over 100 km with an aggregate traffic load of close to 9 Tb/s.

Open Transport Switch (OTS) The Open Transport Switch (OTS) [261] is an OpenFlow enabled optical virtual switch design. The OTS design abstracts the details of the underlying physical switching layer (which could be packet switching or circuit switching) to a virtual switch element. The OTS design introduces three agent modules (discovery, control, and data plane) to interface with the physical switching hardware. These agent modules are controlled from an SDN controller through extended OpenFlow messages. Performance measurements for an example testbed network setup indicate that the circuit path computation latencies on the order of 2–3 s that can be reduced through faster processing in the controller.

Logical xBar The logical xBar [262] has been defined to represent a programmable switch. An elementary (small) xBar could consist of a single OpenFlow switch. Multiple small xBars can be recursively merged to form a single large xBar with a single forwarding table. The xBar concept envisions that xBars are the building blocks for forming large networks. Moreover, labels based on SDN and MPLS are envisioned for managing the xBar data plane forwarding. The xBar concepts have been further advanced in the Orion study [312] to achieve low computational complexity of the SDN control plane.

Optical White Box Nejabati et al. [263] have proposed an optical white box switch design as a building block for a completely softwarized optical network. The optical white box design combines a programmable backplane with programmable switching node elements. More specifically, the backplane consists of two slivers, namely an optical backplane sliver and an electronic backplane sliver. These slivers are set up to allow for flexible arbitrary connections between the switch node elements. The switch node elements include programmable interfaces that build on SDN-controlled BVTs (see Section 2.3.1), protocol agnostic switching, and DSP elements. The protocol agnostic switching element is envisioned to support both wavelength channel and time slot switching in the optical backplane as well as programmable switching with a high-speed packet processor in the electronic backplane. The DSP elements support both the network processing and the signal processing for executing a wide range of network functions. A prototype of the optical white box has been built with only a optical backplane sliver consisting of a 192×192 optical space switch. Experiments have indicated that the creation of a virtual switching node with the OpenDayLight SDN controller takes roughly 400 ms.

GPON Virtual Switch Lee et al. [264] have developed a GPON virtual switch design that makes the GPON fully programmable similar to a conventional OpenFlow switch. Preliminary steps towards the GPON virtual switch design have been taken by Gu et al. [265] who developed components for SDN control of a PON in a data center and Amokrane et al. [266, 267] who developed a module for mapping OpenFlow flow control requests into PON configuration commands. Lee et al. [264] have expanded on this groundwork to abstract the entire GPON into a virtual OpenFlow switch. More specifically, Lee et al. have comprehensively designed a hardware architecture and a software architecture to allow SDN control to interface with the virtual GPON as if it were a standard OpenFlow switch. The experimental performance evaluation of the designed GPON virtual switch measured response times for flow entry modifications from an ONU port (where a subscriber connects to the virtual GPON switch) to an SDN external port around 0.6 ms, which compares to 0.2 ms for a corresponding flow entry modification in a conventional OFsoftswitch and 1.7 ms in a EdgeCore AS4600 switch. In a related study on SDN controlled switching in a PON, Yeh et al. [268] have designed an ONU with an optical switch that selects OFDM subchannels in a TWDM-PON. The switch in the ONU allows for flexible dynamic adaption of the downstream bandwidth through SDN. Gu et al. [313] have examined the flexible SDN controlled re-arrangement of ONUs to OLTs so as to efficiently support PON service with network coding [314].

Flexi Access Network Node A flexi-node for an access network that flexibly aggregates traffic flows from a wide range of networks, such as local area networks and base stations of wireless networks has been proposed in [269]. The flexi-node design is motivated by the shortcomings of the currently deployed core/metro network architectures that attempt to consolidate the access and metro networks. This consolidation forces all traffic in the access network to traverse the metro network, even if the traffic is destined to destination nodes in the coverage area of an access network. In contrast, the proposed flexi-node encompasses electrical and optical forwarding capabilities that can be controlled through SDN. The flexi-node can thus serve as an effective aggregation node in access-metro networks. Traffic that is destined to other nodes in the coverage area of an access network can be sent directly to the access network.

Kondepu et al. have similarly presented an SDN based PON aggregation node [270]. In their architecture, multiple ONUs communicate with the SDN controller within the aggregation node to request the scheduling of upstream transmission resources. ONUs are then serviced by multiple Optical Service Units (OSUs) which exist within the aggregation node alongside with the SDN controller. OSUs are then configured by the controller based on Time and Wavelength Division Multiplexed (TWDM) PON. The OSUs step between normal and sleep-mode depending on the traffic loads, thus saving power.

2.3.3.2 Switching Paradigms

Converged Packet-Circuit Switching Hybrid packet-circuit optical network infrastructures controlled by SDN have been explored in a few studies. Das et al. [271] have described how to unify the control and management of circuit- and packet-switched networks using OpenFlow. Since packet- and circuit-switched networking are extensively employed in optical networks, examining their integration is an important research direction. Das et al. have given a high-level overview of a flow abstraction for each type of switched network and a common control paradigm. In their follow-up work, Das et al. [272] have described how a packet and circuit switching network can be implemented in the context of an OpenFlow-protocol based testbed. The testbed is a standard Ethernet network that could generally be employed in any access network with Time Division Multiplexing (TDM). Veisllari et al. [273] studied packet/circuit hybrid optical long-haul metro access networks. Although Veisllari et al. indicated that SDN can be used for load balancing in the proposed packet/circuit network, no detailed study of such an SDN-based load balancing has been conducted in [273]. Related switching paradigms that integrate SDN with Generalized Multiple Protocol Label Switching (GMPLS) have been examined in [274, 275], while data center specific aspects have been surveyed in [276].

Cerroni et al. [277] have further developed the concept of unifying circuit- and packet-switching networks with OpenFlow, which was initiated by Das et al. [271, 272]. The unification is accomplished with SDN on the network layer and can be used in core networks. Specifically, Cerroni et al. [277] have described an extension of the OpenFlow flow concept to support hybrid networks. OpenFlow message format extensions to include matching rules and flow entries have also been provided. The matching rules can represent different transport functions, such as a channel on which a packet is received in optical circuit-switched WDM networks, time slots in TDM networks, or transport class services (such as guaranteed circuit service or best effort packet service). Cerroni et al. [277] have presented a testbed setup and reported performance results for throughput (in bit/s and packets/s) to demonstrate the feasibility of the proposed unified OpenFlow switching network.

R-LR-UFAN The Reconfigurable Long-Reach UltraFlow Access Network (R-LR-UFAN) [278, 279] provides flexible dual-mode transport service based on either the Internet Protocol (IP) or Optical Flow Switching (OFS). OFS [315] provides dedicated end-to-end network paths through purely optical switching, i.e., there is no electronic processing or buffering at intermediate network nodes. The R-LR-UFAN architecture employs multiple feeder fibers to form subnets within the network. UltraFlow coexists alongside the conventional PON OLT and ONUs. The R-LR-UFAN introduces new entities, namely the Optical Flow Network Unit (OFNU) and the SDN-controlled Optical Flow Line Terminal (OFLT). A Quasi-PAssive Reconfigurable

(QPAR) node [280] is introduced between the OFNU and OFLT. The QPAR node can re-route intra PON traffic between OFNUs without having to pass through the OLFTs. The optically rerouted intra-PON channels can be used for communication between wireless base stations supporting inter cell device-to-device communication. The testbed evaluations indicate that for an intra-PON traffic ratio of 0.3, the QPAR strategy achieves power savings up to 24%.

Flexi-grid The principle of flexi-grid (elastic) optical networking [122, 182–187, 316] has been explored in several SDN infrastructure studies. Generally, flexi-grid networking strives to enhance the efficiency of the optical transmissions by adapting physical (photonic) transmission parameters, such as modulation format, symbol rate, number and spacing of subcarrier wavelength channels, as well as the ratio of forward error correction to payload. Flexi-grid transmissions have become feasible with high-capacity flexible transceivers. Flexi-grid transmissions use narrower frequency slots (e.g., 12.5 GHz) than classical Wavelength Division Multiplexing (WDM, with typically 50 GHz frequency slots for WDM) and can flexibly form optical transmission channels that span multiple contiguous frequency slots.

Cvijetic [281] has proposed a hierarchical flexi-grid infrastructure for multiservice broadband optical access utilizing centralized software-reconfigurable resource management and digital signal processing. The proposed flexi-grid infrastructure incorporates mobile backhaul, as well as SDN controlled transceivers 2.3.1. In follow-up work, Cvijetic et al. [282] have designed a dynamic flexi-grid optical access and aggregation network. They employ SDN to control tunable lasers in the OLT for flexible downstream transmissions. Flexi-grid wavelength selective switches are controlled through SDN to dynamically tune the passband for the upstream transmissions arriving at the OLT. Cvijetic et al. [282] obtained good results for the upstream and downstream bit error rate and were able to provide 150 Mb/s per wireless network cell.

Oliveira et al. [283] have demonstrated a testbed for a Reconfigurable Flexible Optical Network (RFON), which was one of the first physical layer SDN-based testbeds. The RFON testbed is comprised of 4 ROADMs with flexi-grid Wavelength Selective Switching (WSS) modules, optical amplifiers, optical channel monitors and supervisor boards. The controller daemon implements a node abstraction layer and provides configuration details for an overall view of the network. Also, virtualization of the GMPLS control plane with topology discovery and Traffic Engineering (TE)-link instantiation have been incorporated. Instead of using OpenFlow, the RFON testbed uses the controller language YANG [317] to obtain the topology information and collect monitoring data for the lightpaths.

Zhao et al. [284] have presented an architecture with OpenFlow-based optical interconnects for intra-data center networking and OpenFlow-based flexi-grid optical networks for inter-data center networking. Zhao et al. focus on the SDN benefits for inter-data center networking with heterogeneous networks. The proposed architecture includes a service controller, an IP controller, an and optical controller based on the Father Network Operating System (F-NOX) [318, 319]. The performance evaluations in [284] include results for blocking probability, release latency, and bandwidth spectrum characteristics.

2.3.4 Optical Performance Monitoring

2.3.4.1 Cognitive Network Infrastructure

A Cognitive Heterogeneous Reconfigurable Dynamic Optical Network (CHRON) architecture has been outlined in [285, 320, 321]. CHRON senses the current network conditions and adapts the network operation accordingly. The three main components of CHRON are monitoring elements, software adaptable elements, and cognitive processes. The monitoring elements observe two main types of optical transmission impairments, namely non-catastrophic impairments and catastrophic impairments. Non-catastrophic impairments include the photonic impairments that degrade the Optical Signal to Noise Ratio (OSNR), such as the various forms of dispersion, cross-talk, and non-linear propagation effects, but do not completely disrupt the communication. In contrast, a catastrophic impairment, such as a fiber cut or malfunctioning switch, can completely disrupt the communication. Advances in optical performance monitoring allow for in-band OSNR monitoring [322–325] at midpoints in the communication path, e.g., at optical amplifiers and ROADMs.

The cognitive processes involve the collection of the monitoring information in the controller, executing control algorithms, and instructing the software adaptable components to implement the control decisions. SDN can provide the framework for implementing these cognitive processes. Two main types of software adaptable components have been considered so far [286, 287], namely control of transceivers and control of wavelength selective switches/amplifiers. For transceiver control, the cognitive control adjusts the transmission parameters. For instance, transmission bit rates can be adjusted through varying the modulation format or the number of signal carriers in multicarrier communication (see Section 2.3.1).

2.3.4.2 Wavelength Selective Switch/Amplifier Control

In general, ROADMs (see Section 2.3.3.1) employ wavelength selective switches based on filters to add or drop wavelength channels for routing through an optical network. Detrimental non-ideal filtering effects accumulate and impair the OSNR [289]. At the same time, Erbium Doped Fiber Amplifiers (EDFAs) [326] are widely deployed in optical networks to boost optical signal power that has been depleted through attenuation in fibers and ROADMs. However, depending on their operating points, EDFAs can introduce significant noise. Moura et al. [288, 327] have explored SDN based adaptation strategies for EDFA operating points to increase the OSNR. In a complementary study, Paolucci et al. [289] have exploited SDN control to reduce the detrimental filtering effects. Paolucci group wavelength channels that jointly traverse a sequence of filters at successive switching nodes. Instead of passing these wavelength channels through individual (per-wavelength channel) filters, the group of wavelength channels is jointly passed through a superfilter that encompasses all grouped wavelength channels. This joint filtering significantly improves the OSNR.

While the studies [288, 289, 327] have focused on either the EDFA or the filters, Carvalho et al. [290] and Wang et al. [291] have jointly considered the EDFA and filter control. More specifically, the EDFA gain and the filter attenuation (and signal equalization) profile were adapted to improve the OSNR. Carvalho et al. [290] propose and evaluate a specific joint EDFA and filter optimization approach that exploits the global perspective of the SDN controller. The global optimization achieves ONSR improvements close to 5 dB for a testbed consisting of four ROADMs with 100 km fiber links. Wang et al. [291] explore different combinations of EDFA gain control strategies and filter equalization strategies for a simulated network with 14 nodes and 100 km fiber links. They find mutual interactions between the EDFA gain control and the filter equalization control as well as an additional wavelength assignment module. They conclude that global SDN control is highly useful for synchronizing the EDFA gain and filter equalization in conjunction with wavelength assignments so as to achieve improved OSNR.

2.3.5 Infrastructure Layer: Summary and Discussion

The research to date on the SDN controlled infrastructure layer has resulted in a variety of SDN controlled transceivers as well as a few designs of SDN controlled switching elements. Moreover, the SDN control of switching paradigms and optical performance monitoring have been examined. The SDN infrastructure studies have paid close attention to the physical (photonic) communication aspects. Principles of isolation of control plane and data plane with the goals of simplifying network management and making the networks more flexible have been explored. The completed SDN infrastructure layer studies have indicated that the SDN control of the infrastructure layer can reduce costs, facilitate flexible reconfigurable resource management, increase utilizations, and lower latency. However, detailed comprehensive optimizations of the infrastructure components and paradigms that minimize capital and operational expenditures are an important area for future research. Also, further refinements of the optical components and switching paradigms are needed to ease the deployment of SDONs and make the networks operating on the SDON infrastructures more efficient. Moreover, the cost reduction of implementations, easy adoption by network providers, flexible upgrades to adopt new technologies, and reduced complexity require thorough future research.

Most SDON infrastructure studies have focused on a particular network component or networking aspect, e.g., a transceiver or the hybrid packet-circuit switching paradigm, or a particular application context, e.g., data center networking. Future research should comprehensively examine SDON infrastructure components and paradigms to optimize their interactions for a wide set of networking scenarios and application contexts.

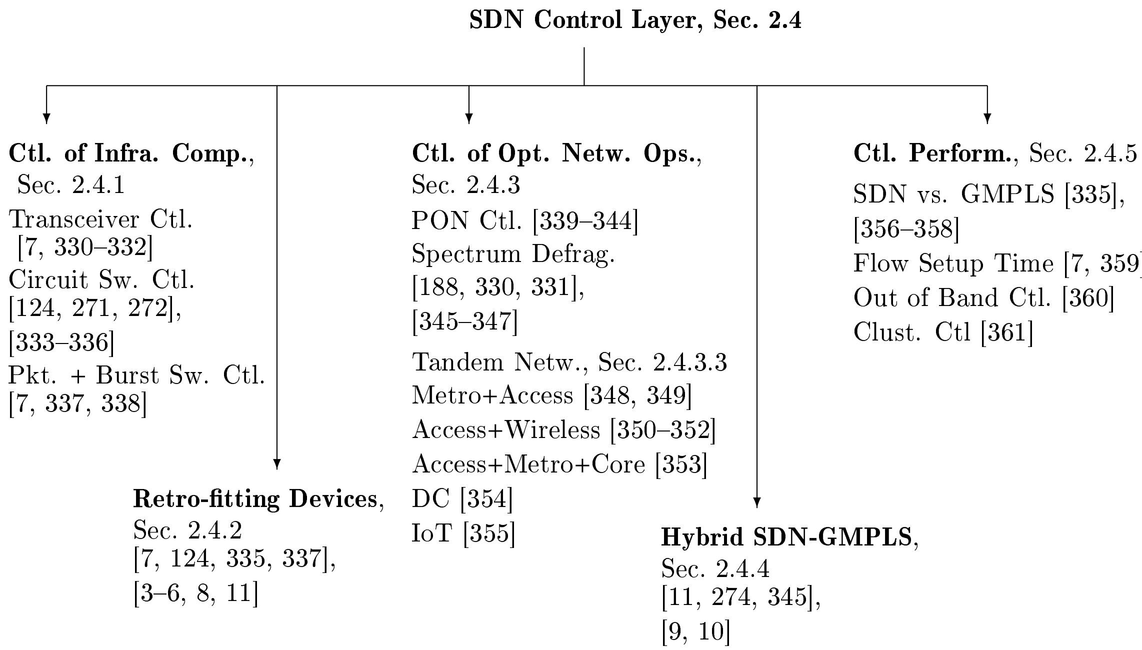


Figure 2.6: Classification of SDON control layer studies.

The SDON infrastructure studies to date have primarily focused on the optical transmission medium. Future research should explore complementary infrastructure components and paradigms to support transmissions in hybrid fiber-wireless and other hybrid fiber-X networks, such as fiber-Digital Subscriber Line (DSL) or fiber-coax cable networks [205, 328, 329]. Generally, the flexible SDN control can be very advantageous for hybrid networks composed of heterogeneous network segments. The OpenFlow protocol can facilitate the topology abstraction of the heterogeneous physical transmission media, which in turn facilitates control and optimization at the higher network protocol layers.

2.4 SDN CONTROL LAYER

This section surveys the SDON studies that are focused on applying the SDN principles at the SDN control layer to control the various optical network elements and operational aspects. The main challenges of SDON control include extensions of the OpenFlow protocol for specifically controlling the optical transmission and switching components surveyed in Section 2.3 and for controlling the optical spectrum as well as for controlling optical networks spanning multiple optical network tiers (see Section 2.2.4.2). As illustrated in Fig. 2.6, we first survey SDN control mechanisms and frameworks for controlling infrastructure layer components, namely transceivers as well as optical circuit, packet, and burst switches. More specifically, we survey OpenFlow extensions for controlling the optical infrastructure components. We then survey mechanisms for retro-fitting non-SDN optical network elements so that they can be controlled by OpenFlow. The retro-fitting typically involves the insertion of an abstraction layer into the network elements. The abstraction layer makes the optical hardware controllable by OpenFlow. The retro-fitting studies would also fit into Section 2.3 as the abstraction layer is inserted into the network elements; however, the abstraction mechanisms closely relate to the OpenFlow extensions for optical networking and we include the retro-fitting studies therefore in this control layer section. We then survey the various SDN control mechanisms for operational aspects of optical networks, including the control of tandem networks that include optical segments. Lastly, we survey SDON controller performance analysis studies.

2.4.1 SDN Control of Optical Infrastructure Components

2.4.1.1 Controlling Optical Transceivers with OpenFlow

Recent generations of optical transceivers utilize digital signal processing techniques that allow many parameters of the transceiver to be software controlled (see Sections 2.3.1.1 and 2.3.1.2). These parameters include modulation scheme, symbol rate, and wavelength. Yu et al. [330] and Chen et al. [331] proposed adding a "modulation format" field to the OpenFlow cross-connect table entries to support this programmable feature of some software defined optical transceivers.

Ji et al. [332] created a testbed that places super-channel optical transponders and optical amplifiers under SDN control. An OpenFlow extension is proposed to control these devices. The modulation technique and FEC code for each optical subcarrier of the super-channel transponder and the optical amplifier power level can be controlled via OpenFlow. Ji et al. do not discuss this explicitly but the transponder subcarriers can be treated as OpenFlow switch ports that can be configured through the OpenFlow protocol via port modification messages. It is unclear in [332] how the amplifiers would be controlled via OpenFlow. However, doing so would allow the SDN controller to adaptively modify amplifiers to compensate for channel impairments while minimizing energy consumption. Ji et al. [332] have established a testbed demonstrating the placement of transponders and EDFA optical amplifiers under SDN control.

Liu et al. [7] propose configuring optical transponder operation via flow table entries with new transponder specific fields (without providing details). They also propose capturing failure alarms from optical transponders and sending them to the SDN controller via OpenFlow Packet-In messages. These messages are normally meant to establish new flow connections. Alternatively, a new OpenFlow message type could be created for the purpose of capturing failure alarms [7]. With failure alarm information, the SDN controller can implement protection switching services.

2.4.1.2 Controlling Optical Circuit Switches with OpenFlow

Circuit switching can be enabled by OpenFlow by adding new circuit switching flow table entries [271, 272, 333, 336]. The OpenFlow circuit switching addendum [334] discusses the addition of cross-connect tables for this purpose. These cross-connect tables are configured via OpenFlow messages inside the circuit switches. According to the addendum, a cross-connect table entry consists of the following fields to identify the input:

- Input Port

- Input Wavelength
- Input Time Slot
- Virtual Concatenation Group

and the following fields to identify the output:

- Output Port
- Output Wavelength
- Output Time Slot
- Virtual Concatenation Group

These cross-connect tables cover circuit switching in space, fixed-grid wavelength, and time.

Channegowda et al. [124, 335] extend the capabilities of the OpenFlow circuit switching addendum to support flexible wavelength grid optical switching. Specifically, the wavelength identifier specified in the circuit switching addendum to OpenFlow is replaced with two fields: *center frequency*, and *slot width*. The *center frequency* is an integer specifying the multiple of 6.25 GHz the center frequency is away from 193.1 Thz and the *slot width* is a positive integer specifying the spectral width in multiples of 12.5 GHz.

An SDN controlled optical network testbed at the University of Bristol has been established to demonstrate the OpenFlow extensions for flexible grid DWDM [124]. The testbed consists of both fixed-grid and flexible-grid optical switching devices. South Korea Telekom has also built an SDN controlled optical network testbed [362].

2.4.1.3 Controlling Optical Packet and Burst Switches with OpenFlow

OpenFlow flow tables can be utilized in optical packet switches for expressing the forwarding table and its computation can be offloaded to an SDN controller. This offloading can simplify the design of highly complex optical packet switches [337].

Cao et al. [337] extend the OpenFlow protocol to work with Optical Packet Switching (OPS) devices by creating: (*i*) an abstraction layer that converts OpenFlow configuration messages to the native OPS configuration, (*ii*) a process that converts optical packets that do not match a flow table entry to the electrical domain for forwarding to the SDN controller, and (*iii*) a wavelength identifier extension to the flow table entries. To compensate for either the lack of any optical buffering or limited optical buffering, an SDN controller, with its global view, can provide more effective means to resolve contention that would lead to packet loss in optical packet switches. Specifically, Cao et al. suggest to select the path with the most available resources among multiple available paths between two nodes [337]. Paths can be re-computed periodically or on-demand to account for changes in traffic conditions. Monitoring messages can be defined to keep the SDN controller updated of network traffic conditions.

Engineers with Japan's National Institute of Information and Communications Technology [338] have created an optical circuit and packet switched demonstration system in which the packet portion is SDN controlled. The optical circuit switching is implemented with Wavelength Selective Switches (WSSs) and the optical packet switching is implemented with an Semiconductor Optical Amplifier (SOA) switch.

OpenFlow flow tables can also be used to configure optical burst switching devices [7]. When there is no flow table entry for a burst of packets, the optical burst switching device can send the Burst Header Packet (BHP) to the SDN controller to process the addition of the new flow to the network [7] rather than the first packet in the burst.

2.4.2 Retro-fitting Devices to Support OpenFlow

An abstraction layer can be used to turn non-SDN optical switching devices into OpenFlow controllable switching devices [7, 11, 124, 335, 337]. As illustrated in Fig. 2.7, the abstraction layer provides a conversion layer between OpenFlow configuration messages and the optical switching devices' native management interface, e.g., the Simple Network Management Protocol (SNMP), the Transaction Language 1 (TL1) protocol, or a proprietary (vendor-specific) API. Additionally, a virtual OpenFlow switch with virtual interfaces that correspond to physical switching ports on the non-SDN switching device completes the abstraction layer [3–7]. When a flow entry is added between two virtual ports in the virtual OpenFlow switch, the abstraction layer uses the switching devices' native management interface to add the flow entry between the two corresponding physical ports.

A non-SDN PON OLT can be supplemented with a two-port OpenFlow switch and a hardware abstraction layer that converts OpenFlow forwarding rules to control messages understood by the non-SDN OLT [8]. Fig. 2.8 illustrates this OLT retro-fit for SDN control via OpenFlow. In this way the PON has its switching functions controlled by OpenFlow.

2.4.3 SDN Control of Optical Network Operation

2.4.3.1 Controlling Passive Optical Networks with OpenFlow

An SDN controlled PON can be created by upgrading OLTs to SDN-OLTs that can be controlled using a Southbound Interface, such as OpenFlow [339, 340]. A centralized PON controller, potentially executing in a data center, controls one or more

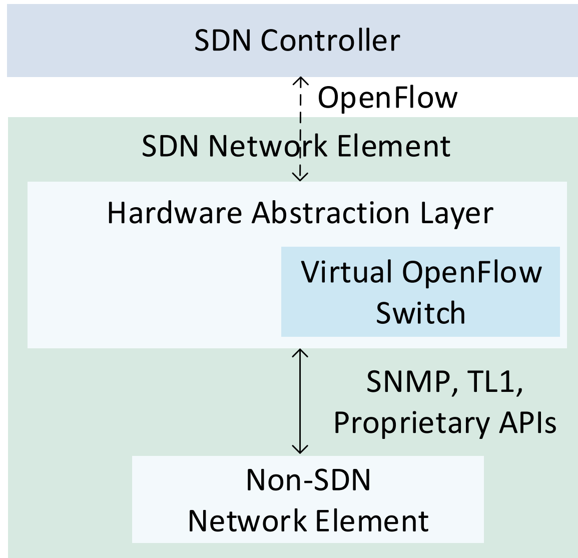


Figure 2.7: Traditional non-SDN network elements can be retro-fitted for control by an SDN controller using OpenFlow using a hardware abstraction layer [3–7].

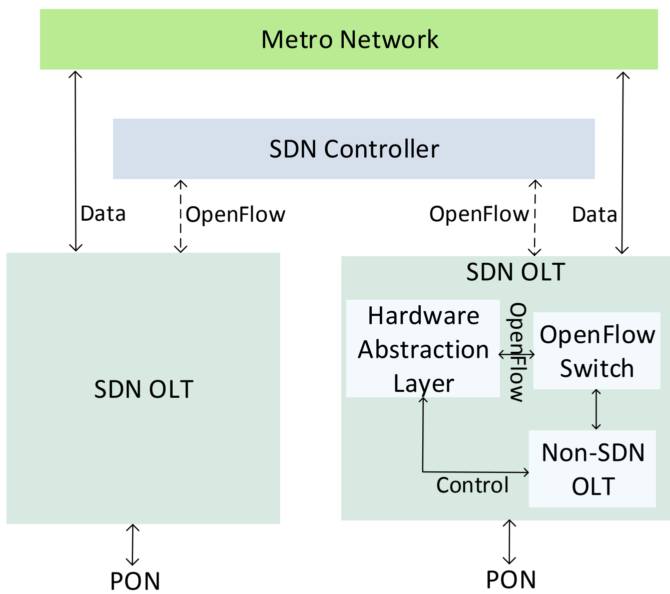


Figure 2.8: Non-SDN OLTs can be retro-fitted for control by an SDN controller using OpenFlow [8].

SDN-OLTs. The advantage of using SDN is the broadened perspective of the PON controller as well as the potentially reduced cost of the SDN-OLT compared to a non-SDN OLT.

Parol and Pawlowski [341, 342] define OpenFlowPLUS to extend the OpenFlow SBI for GPON. OpenFlowPLUS extends SDN programmability to both OLT and ONU devices whereby each act as an OpenFlow switch through a programmable flow table. Non-switching functions (e.g., ONU registration, dynamic bandwidth allocation) are outside the scope of OpenFlowPLUS. OpenFlowPLUS extends OpenFlow by channeling OpenFlow messages through the GPON ONU Management and Control Interface (OMCI) control channel and adding PON specific action instructions to flow table entries. The PON specific action instructions defined in OpenFlowPLUS are:

- (new *gpon* action type): map matching packets to PON specific traffic identifiers, e.g., GPON Encapsulation Method (GEM) ports and GPON Traffic CONTainers (T-CONTs)
- (*output* action type): activate PON specific framing of matching packets

Many of the OLT functions operate at timescales that are problematic for the controller due to the latency between the controller and OLTs. However, Khalili et al. [339] identify ONU registration policy and coarse timescale DBA policy as functions that operate at timescales that allow effective offloading to an SDN controller. Yan et al. [343] further identify OLT and ONU power control for energy savings as a function that can be effectively offloaded to an SDN controller.

There is also a movement to use PONs in edge networks to provide connectivity inside a multitenant building or on a campus with multiple buildings [341, 342]. The use of PONs in this edge scenario requires rapid re-provisioning from the OLT. A software controlled PON can provide this needed rapid reprovisioning [341, 342].

Kanonakis et al. [344] propose leveraging the broad perspective that SDN can provide to perform dynamic bandwidth allocation across several Virtual PONs (VPONs). The VPONs are separated on a physical PON by the wavelength bands that they utilize. Bandwidth allocation is performed at the granularity of OFDMA subcarriers that compose the optical spectrum.

2.4.3.2 SDN Control of Optical Spectrum Defragmentation

In a departure from the fixed wavelength grid (ITU-T G.694.1), elastic optical networking allows flexible use of the optical spectrum. This flexibility can permit higher spectral efficiency by avoiding consuming an entire fixed-grid wavelength channel when unnecessary and avoiding unnecessary guard bands in certain circumstances [188]. However, this flexibility causes fragmentation of the optical spectrum as flexible grid lightpaths are established and terminated over time.

Spectrum fragmentation leads to the circumstance in which there is enough spectral capacity to satisfy a demand but that capacity is spread over several fragments rather than being consolidated in adjacent spectrum as required. If the fragmentation is not counter-acted by a periodic defragmentation process than overall spectral utilization will suffer. This resource fragmentation problem appears in computer systems in main memory and long term storage. In those contexts the problem is typically solved by allowing the memory to be allocated using non-adjacent segments. Memory and storage is partitioned into pages and blocks, respectively. The allocations of pages to a process or blocks to a file do not need to be contiguous. With communication spectrum this would mean combining multiple small bandwidth channels through inverse multiplexing to create a larger channel [345].

An SDN controller can provide a broad network perspective to empower the periodic optical spectrum defragmentation process to be more effective [345]. In general, optical spectrum defragmentation operations can reduce lightpath blocking probabilities from 3% [330] up to as much as 75% [331, 346]. Multicore fibers provide additional spectral resources through additional transmission cores to permit quasi-hitless defragmentation [347].

2.4.3.3 SDN Control of Tandem Networks

Metro and Access Wu et al. [348, 349] propose leveraging the broad perspective that SDN can provide to improve bandwidth allocation. Two cooperating stages of SDN controllers: (*i*) access stage that controls each SDN OLT individually, and (*ii*) metro stage that controls global bandwidth allocation strategy, can coordinate bandwidth allocation across several physical PONs [348, 349]. The bandwidth allocation is managed cooperatively among the two stages of SDN controllers to optimize the utilization of the access and metro network bandwidth. Simulation experiments indicate a 40% increase in network bandwidth utilization as a result of the global coordination compared to operating the bandwidth allocation only within the individual PONs [348, 349].

Access and Wireless Bojic et al. [350] expand on the concept of SDN controlled OFDMA enabled VPONs [344] to provide mobile backhaul service. The backhaul service can be provided for wireless small-cell sites (e.g., micro and femto cells) that utilize millimeter wave frequencies. Each small-cell site contains an OFDMA-PON ONU that provides the backhaul service through the access network over a VPON. An SDN controller is utilized to assign bandwidth to each small-cell site through OFDMA subcarrier assignment in a VPON to the constituent ONU. The SDN controller leverages its broad view of the network to provide solutions to the joint bandwidth allocation and routing across several network segments. With this broad perspective of the network, the SDN controller can make globally rather than just locally optimal bandwidth allocation and routing decisions. Efficient optimization algorithms, such as genetic algorithms, can be used to provide computationally efficient competitive solutions, mitigating computational complexity issues associated with optimization for large networks. Additionally, network partitioning with an SDN controller for each partition can be used to mitigate unreasonable computational complexity that arises when scaling to large networks. Tanaka and Cvijetic [351] presented one such optimization formulation for maximizing throughput.

Costa-Requena et al. [352] described a proof-of-concept LTE testbed they have constructed whereby the network consists of software defined base stations and various network functions executing on cloud resources. The testbed is described in broad qualitative terms, no technical details are provided. There was no mathematical or experimental analysis provided.

Access, Metro, and Core Slyne and Ruffini [353] provide a use case for SDN switching control across network segments: use Layer 2 switching across the access, metro, and core networks. Layer 2 (e.g., Ethernet) switching does not scale well due to a lack of hierarchy in its addresses. That lack of hierarchy does not allow for switching rules on aggregates of addresses thereby limiting the scaling of these networks. Slyne and Ruffini [353] propose using SDN to create hierarchical pseudo-MAC addresses that permit a small number of flow table entries to configure the switching of traffic using Layer 2 addresses across network segments. The pseudo-MAC addresses encode information about the device location to permit simple switching rules. At the entry of the network, flow table entries are set up to translate from real (non-hierarchical) MAC addresses to hierarchical pseudo-MAC addresses. The reverse takes place at the exit point of the network.

DC Virtual Machine Migration Mandal et al. [354] provided a cloud computing use case for SDN bandwidth allocation across network segments: Virtual Machine (VM) migration between data centers. VM migrations require significant network bandwidth. Bandwidth allocation that utilizes the broad perspective that SDN can provide is critical for reasonable VM migration latencies without sacrificing network bandwidth utilization.

Internet of Things Wang et al. [355] examine another use case for SDN bandwidth allocation across network segments: the Internet of Things (IoT). Specifically, Wang et al. have developed a Dynamic Bandwidth Allocation (DBA) protocol that exploits SDN control for multicasting and suspending flows. This DBA protocol is studied in the context of a virtualized WDM optical access network that provides IoT services through the distributed ONUs to individual devices. The SDN controller employs multicasting and flow suspension to efficiently prioritize the IoT service requests. Multicasting allows multiple requests to share resources in the central nodes that are responsible for processing a prescribed wavelength in the central office (OLT). Flow suspension allows high-priority requests (e.g., an emergency call) to suspend ongoing low-priority traffic flows (e.g., routine meter readings). Performance results for a real-time SDN controller implementation indicate that the proposed bandwidth (resource) allocation with multicast and flow suspension can improve several key performance metrics, such as request serving ratio, revenue, and delays by 30–50 % [355].

2.4.4 Hybrid SDN-GMPLS Control

2.4.4.1 Generalized MultiProtocol Label Switching (GMPLS)

Prior to SDN, MultiProtocol Label Switching (MPLS) offered a mechanism to separate the control and data planes through label switching. With MPLS, packets are forwarded in a connection-oriented manner through Label Switched Paths (LSPs) traversing Label Switching Routers (LSRs). An entity in the network establishes an LSP through a network of LSRs for a particular class of packets and then signals the label-based forwarding table entries to the LSRs. At each hop along an LSP, a packet is assigned a label that determines its forwarding rule at the next hop. At the next hop, that label determines that packet's output port and label for the next hop; the process repeats until the packet reaches the end of the LSP. Several signalling protocols for programming the label-based forwarding table entries inside LSRs have been defined, e.g., through the Resource Reservation Protocol (RSVP). Generalized MPLS (GMPLS) extends MPLS to offer circuit switching capability. Although never commercially deployed [7], GMPLS and a centralized Path Computation Element (PCE) [363–366] have been considered for control of optical networks.

2.4.4.2 Path Computation Element (PCE)

A PCE is a concept developed by the IETF (see RFC 4655) to refer to an entity that computes network paths given a topology and some criteria. The PCE concept breaks the path computation action from the forwarding action in switching devices. A PCE could be distributed in every switching element in a network domain or there could be a single centralized PCE for an entire network domain. The network domain could be an area of an Autonomous System (AS), an AS, a conglomeration of several ASes, or just a group of switching devices relying on one PCE. Some of an SDN controller's functionality falls under the classification of a centralized PCE. However, the PCE concept does not include the external configuration of forwarding tables. Thus, a centralized PCE device does not necessarily have a means to configure the switching elements to provision a computed path.

When the entity requesting path computation is not co-located with the PCE, a PCE Communication Protocol (PCEP) is used over TCP port 4189 to facilitate path computation requests and responses. The PCEP consists of the following message types:

- Session establishment messages (open, keepalive, close)
- PCReq – Path computation request
- PCRep – Path computation reply
- PCNtf – event notification
- PCErr – signal a protocol error

The path computation request message must include the end points of the path and can optionally include the requested bandwidth, the metric to be optimized in the path computation, and a list of links to be included in the path. The Path computation reply includes the computed path expressed in the Explicit Route Object format (see RFC 3209) or an indication that there is no path. See RFC 5440 for more details on PCEP.

A PCE has been proposed as a central entity to manage a GMPLS-enabled optical circuit switched network. Specifically, the PCE maintains the network topology in a structure called the Traffic Engineering Database (TED). The traffic engineering modifier (see RFC 2702) signifies that the path computations are made to relieve congestion that is caused by the sub-optimal allocation of network resources. This modifier is used extensively in discussions of MPLS/GMPLS because their use case is for traffic engineering; in acronym form the modifier is TE (e.g., TE LSP, RSVP-TE).

If the PCE is stateful with complete control over its network domain, it will also maintain an LSP database recording the provisioned GMPLS lightpaths. A lightpath request can be sent to the PCE, it will use the topology and LSP database to find the optimal path and then configure the GMPLS-controlled optical circuit switching nodes using NETCONF (see RFC 6241) or proprietary command line interfaces (CLIs) [345]. This stateful PCE with instantiation capabilities (capabilities to provision lightpaths) operates similarly to an SDN controller. For that reason, GMPLS with a centralized stateful PCE with instantiation capabilities can provide a baseline for performance analysis of an SDN controller as well as provide a mechanism to be blended with an SDN controller for hybrid control [11, 124, 335].

2.4.4.3 Approaches to Hybrid SDN-GMPLS Control

Hybrid GMPLS/PCE and SDN control can be formed by allowing an SDN controller to leverage a centralized PCE to control a portion of the infrastructure using PCEP as the SBI [274, 345]; see illustration a) in Fig. 2.9. The SDN controller builds higher functionality above what the PCE provides and can possibly control a large network that utilizes several PCEs as well as OpenFlow controlled network elements.

Alternatively, the SDN controller can leverage a PCE for its path computation abilities with the SDN controller handling the configuration of the network elements to establish a path using an SBI protocol, such as OpenFlow [9–11]; see illustration b) in Fig. 2.9.

2.4.5 SDN Performance Analysis

2.4.5.1 SDN vs. GMPLS

Liu et al. [356] provided a qualitative comparison of GMPLS, GMPLS/PCE, and SDN OpenFlow for control of wavelength switched optical networks. Liu et al. noted that there is an evolution of centralized control from GMPLS to GMPLS/PCE to OpenFlow. Whereas GMPLS offers distributed control, GMPLS/PCE is commonly regarded as having centralized path computation but still distributed provisioning/configuration; while OpenFlow centralizes all of the network control. In our

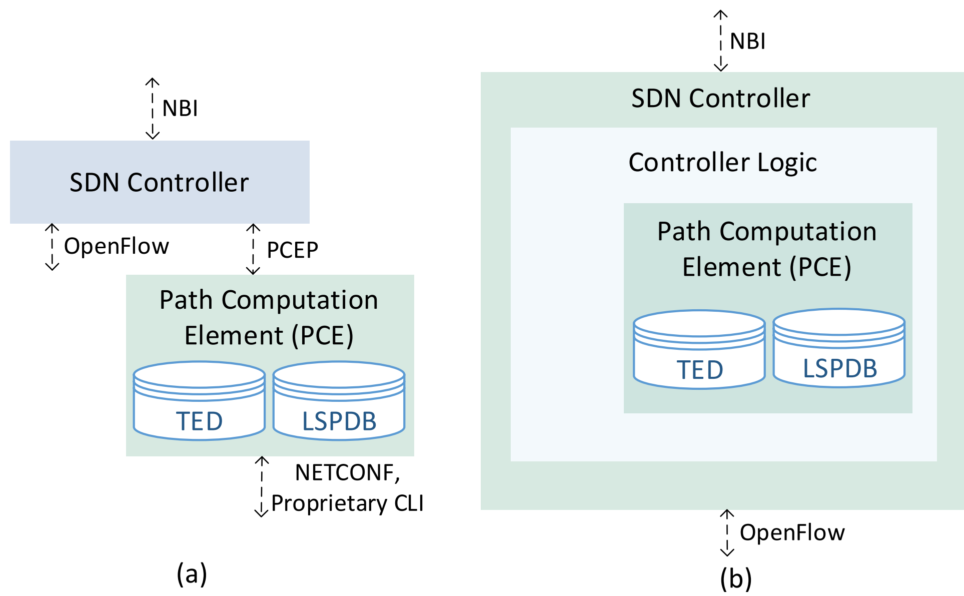


Figure 2.9: Hybrid GMPLS/PCE and SDN network control [9–11].

discussion in Section 2.4.4 we noted that a stateful PCE with instantiation capabilities centralizes all network control and is therefore very similar to SDN. Liu et al. have also pointed out that GMPLS/PCE is more technically mature compared to OpenFlow with IETF RFCs for GMPLS (see RFC 3471) and PCE (see RFC 4655) that date back to 2003 and 2006, respectively. SDN has just recently, in 2014, received standardization attention from the IETF (see RFC 7149).

A comparison of GMPLS and OpenFlow has been conducted by Zhao et al. [357] for large-scale optical networks. Two testbeds were built, based on GMPLS and on Openflow, respectively. Performance metrics, such as blocking probability, wavelength utilization, and lightpath setup time were evaluated for a 1000 node topology. The results indicated that GMPLS gives slightly lower blocking probability. However, OpenFlow gives higher wavelength utilization and shorter average lightpath setup time. Thus, the results suggest that OpenFlow is overall advantageous compared to GMPLS in large-scale optical networks.

Cvijetic et al. [358] conducted a numerical analysis to compare the computed shortest path lengths for non-SDN, partial-SDN, and full-SDN optical networks. A full-SDN network enables path lengths that are approximately a third of those computed on a non-SDN network. These path lengths can also translate into an energy consumption measure, with shortest paths resulting in reduced energy consumption. An SDN controlled network can result in smaller computed shortest paths that translates to smaller network latency and energy consumption [358].

Experiments conducted on the testbed described in [335] show a 4 % reduction in lightpath blocking probability using SDN OpenFlow compared to GMPLS for lightpath provisioning. The same experiments show that lightpath setup times can be reduced to nearly half using SDN OpenFlow compared to GMPLS. Finally, the experiments show that an Open vSwitch based controller can process about three times the number of flows per second as a NOX [318] based controller.

2.4.5.2 SDN Controller Flow Setup

Veisllari et al. [359] evaluated the use of SDN to support both circuit and packet switching in a metropolitan area ring network that interconnects access network segments with a backbone network. This network is assumed to be controlled by a single SDN controller. The objective of the study [359] was to determine the effect of packet service flow size on the required SDN controller flow service time to meet stability conditions at the controller. Toward this end, Veisllari et al. produced a mean arrival rate function of new packet and circuit flows at that controller. This arrival rate function was visualized by varying the length of short-lived ("mice") flows, the fraction of long-lived ("elephant") flows, and the volume of traffic consumed by "elephant" flows. Veisllari et al. discovered, through these visualizations, that the length of "mice" flows is the dominating parameter in this model.

Veisllari et al. translated the arrival rate function analysis to an analysis of the ring MAN network dimensions that can be supported by a single SDN controller. The current state-of-the-art Beacon controller can handle a flow request every 571 ns. Assuming mice flows sizes of 20 kB and average circuit lifetimes of 1 second, as the fraction of packet traffic increases from 0.1 to 0.9, the network dimension supported by a single Beacon SDN controller decreases from 14 nodes with 92 wavelengths per node to 5 nodes with 10 wavelengths per node.

Liu et al. [7] use a multinational (Japan, China, Spain) NOX:OpenFlow controlled four-wavelength optical circuit and burst switched network to study path setup/release times as well as path restoration times. The optical transponders that can generate failure alarms were also under NOX:OpenFlow control and these alarms were used to trigger protection switching. The single SDN controller was located in the Japanese portion of the network. The experiments found the path setup time to vary from 250–600 ms and the path release times to vary from 130–450 ms. Path restoration times varied from 250–500 ms. Liu et al. noted that the major contributing factor to these times was the OpenFlow message delivery time [7].

2.4.5.3 Out of Band Control

Sanchez et al. [360] have qualitatively compared four SDN controlled ring metropolitan network architectures. The architectures vary in whether the SDN control traffic is carried in-band with the data traffic or out-of-band separately from the data traffic. In a single wavelength ring network, out-of-band control would require a separate physical network that would come at a high cost, but provide reliability of the network control under failure of the ring network. In a multiwavelength ring network, a separate wavelength can be allocated to carry the control traffic. Sanchez et al. [360] focused on a Tunable Transceiver Fixed Receiver (TTFR) WDM ring node architecture. In this architecture each node receives data on a home wavelength channel and has the capability to transmit on any of the available wavelengths to reach any other node. The addition of the out-of-band control channel on a separate wavelength requires each node to have an additional fixed receiver, thereby increasing cost. Sanchez et al. identified a clear tradeoff between cost and reliability when comparing the four architectures.

2.4.5.4 Clustered SDN Control

Penna et al. [361] described partitioning a wavelength-switched optical network into administrative domains or clusters for control by a single SDN controller. The clustering should meet certain performance criteria for the SDN controller. To permit lightpath establishment across clusters, an inter-cluster lightpath establishment protocol is established. Each SDN controller provides a lightpath establishment function between any two points in its associated cluster. Each SDN controller also keeps a global view of the network topology. When an SDN controller receives a lightpath establishment request whose computed path traverses other clusters, the SDN controller requests lightpath establishment within those clusters via a WBI.

The formation of clusters can be performed such that for a specified number of clusters the average distance to each SDN controller is minimized [361]. The lightpath establishment time decreases exponentially as the number of clusters increases.

2.4.6 Control Layer: Summary and Discussion

A very large body of literature has explored how to expand the OpenFlow protocol to support various optical network technologies (e.g., optical circuit switching, optical packet switching, passive optical networks). A significant body of literature has investigated methodologies for retro-fitting non-SDN network elements for OpenFlow control as well as integrating SDN/OpenFlow with the GMPLS/PCE control frame-

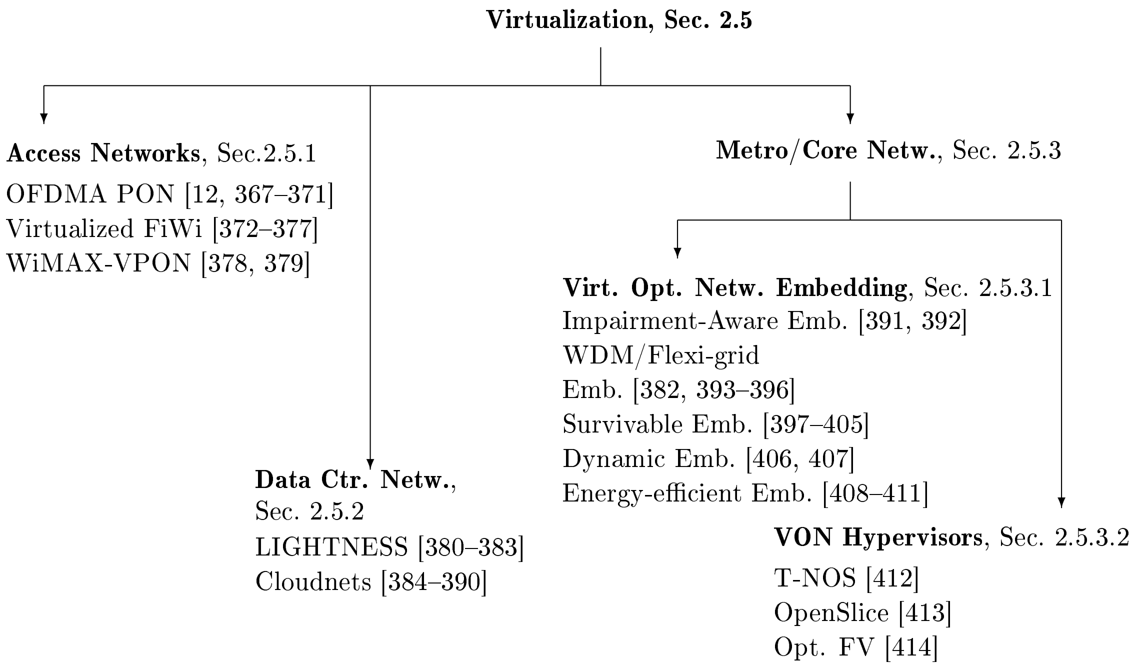
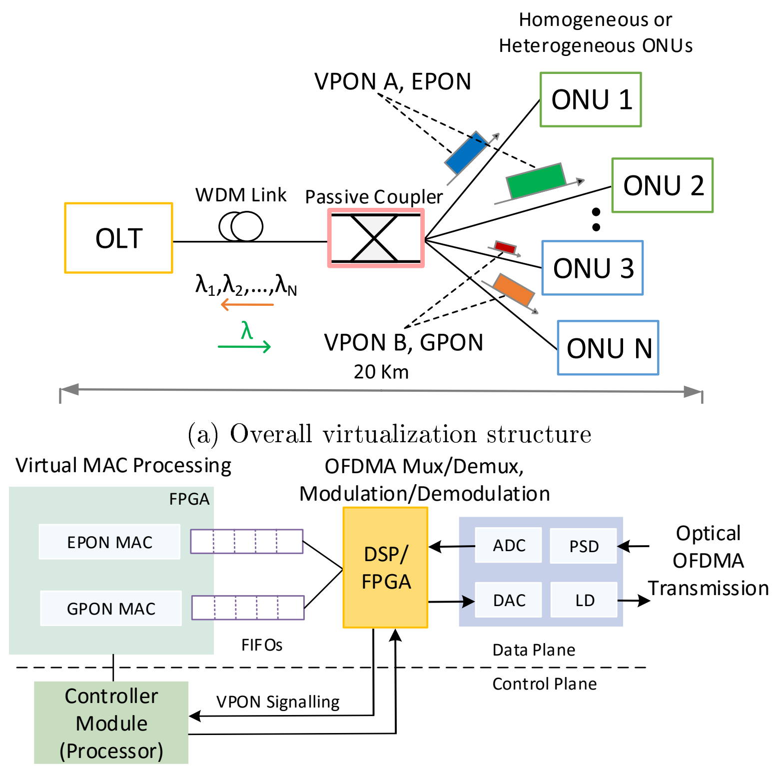


Figure 2.10: Classification of SDON virtualization studies.

work. A variety of SDN controller use cases have been identified that motivate the benefits of the centralized network control made possible with SDN (e.g., bandwidth allocation over large numbers of subscribers, controlling tandem networks).

However, analyzing the performance of SDN controllers for optical network applications is still in a state of infancy. It will be important to understand the connection between the implementation of the SDN controller (e.g., processor core architecture, number of threads, operating system) and the network it can effectively control (e.g., network traffic volume, network size) to meet certain performance objectives (e.g., maximum flow setup time). At present there are not enough relevant studies to gain an understanding of this connection. With this understanding network service providers will be able to partition their networks into control domains in a manner that meets their performance objectives.



(a) Overall virtualization structure

(b) Virtualization of OLT

Figure 2.11: Illustration of OFDMA based virtual access network [12].

2.5 VIRTUALIZATION

This section surveys control layer mechanisms for virtualizing SDONs. As optical infrastructures have typically high costs, creating multiple VONs over the optical network infrastructure is especially important for access networks, where the costs need to be amortized over relatively few users. Throughout, accounting for the specific optical transmission and signal propagation characteristics is a key challenge for SDON virtualization. Following the classification structure illustrated in Fig. 2.10, we initially survey virtualization mechanisms for access networks and data center networks, followed by virtualization mechanisms for optical core networks.

2.5.1 Access Networks

2.5.1.1 OFDMA Based PON Access Network Virtualization

Wei et al. [12, 367, 368] have developed a link virtualization mechanism that can span from optical access to backbone networks based on Orthogonal Frequency Division Multiplexing Access (OFDMA). Specifically, for access networks, a Virtual PON (VPON) approach based on multicarrier OFDMA over WDM has been proposed. Distinct network slices (VPONs) utilize distinct OFDMA subcarriers, which provide a level of isolation between the VPONs. Thus, different VPONs may operate with different MAC standards, e.g., as illustrated in Fig. 2.11(a), VPON A may operate as an Ethernet PON (EPON) while VPON B operates as a Gigabit PON (GPON). In addition, virtual MAC queues and processors are isolated to store and process the data from multiple VPONs, thus creating virtual MAC protocols, as illustrated in Fig. 2.11(b). The OFDMA transmissions and receptions are processed in a DSP module that is controlled by a central SDN control module. The central SDN control module also controls the different virtual MAC processes in Fig. 2.11(b), which feed/receive data to/from the DSP module. Additional bandwidth partitioning between VPONs can be achieved through Time Division Multiple Access (TDMA). Simulation studies compared a static allocation of subcarriers to VPONs with a dynamic allocation based on traffic demands. The dynamic allocation achieved significantly higher numbers of supported VPONs on a given network infrastructure as well as lower packet delays than the static allocation. A similar strategy for flexibly employing different dynamic bandwidth allocation modules for different groups of ONU queues has been examined in [369].

Similar OFDMA based slicing strategies for supporting cloud computing have been examined by Jinno et al. [370]. Zhou et al. [371] have explored a FlexPON with similar virtualization capabilities. The FlexPON employs OFDM for adaptive transmissions. The isolation of different VPONs is mainly achieved through separate MAC processing. The resulting VPONs allow for flexible port assignments in ONUs and OLT, which have been demonstrated in a testbed [371].

2.5.1.2 FiWi Access Network Virtualization

Virtualized FiWi Network Dai et al. [372–374] have examined the virtualization of FiWi networks [415, 416] to eliminate the differences between the heterogeneous segments (fiber and wireless). The virtualization provides a unified homogenous (virtual) view of the FiWi network. The unified network view simplifies flow control and other operational algorithms for traffic transmissions over the heterogeneous network segments. In particular, a virtual resource manager operates the heterogeneous segments. The resource manager permits multiple routes from a given source node to a given destination node. Load balancing across the multiple paths has been examined in [375, 376]. Simulation results indicate that the virtualized FiWi network with load balancing significantly reduces packet delays compared to a conventional FiWi network. An experimental OpenFlow switch testbed of the virtualized FiWi network has been presented in [377]. Testbed measurements demonstrate the seamless networking across the heterogeneous fiber and wireless networks segments. Measurements for nodal throughput, link bandwidth utilization, and packet delay indicate performance improvements due to the virtualized FiWi networking approach. Moreover, the FiWi testbed performance is measured for a video service scenario indicating that the virtualized FiWi networking approach improves the Quality of Experience (QoE) [417, 418] of the video streaming. A mathematical performance model of the virtualized FiWi network has been developed in [377].

WiMAX-VPON WiMAX-VPON [378, 379] is a Layer-2 Virtual Private Network (VPN) design for FiWi access networks. WiMAX-VPON executes a common MAC protocol across the wireless and fiber network segments. A VPN based admission control mechanism in conjunction with a VPN bandwidth allocation ensures per-flow Quality of Service (QoS). Results from discrete event simulations demonstrate that the proposed WiMAX-VPON achieves favorable performance. Also, Dhaini et al. [378, 379] demonstrate how the WiMAX-VPON design can be extended to different access network types with polling-based wireless and optical medium access control.

2.5.2 Data Centers

2.5.2.1 LIGHTNESS

LIGHTNESS [380–383] is a European research project examining an optical Data Center Network (DCN) capable of providing dynamic, programmable, and highly available DCN connectivity services. Whereas conventional DCNs have rigid control and management platforms, LIGHTNESS strives to introduce flexible control and management through SDN control. The LIGHTNESSS architecture comprises server racks that are interconnected through optical packet switches, optical circuit switches, and hybrid Top-of-the-Rack (ToR) switches. The server racks and switches are all controlled and managed by an SDN controller. LIGHTNESS control consists of an SDN controller above the optical physical layer and OpenFlow agents that interact with the optical network and server elements. The SDN controller in cooperation with the OpenFlow-agents provides a programmable data plane to the virtualization modules. The virtualization creates multiple Virtual Data Centers (VDCs), each with its own virtual computing and memory resources, as well as virtual networking resources, based on a given physical data center. The virtualization is achieved through a VDC planner module and an NFV application that directly interact with the SDN controller. The VDC planner composes the VDC slices through mapping of the VDC requests to the physical SDN-controlled switches and server racks. The VDC slices are monitored by the NFV application, which interfaces with the VDC planner. Based on monitoring data, the NFV application and VDC planner may revise the VDC composition, e.g., transition from optical packet switches to optical circuit switches.

2.5.2.2 Cloudnets

Cloudnets [419–424] exploit network virtualization for pooling resources among distributed data centers. Cloudnets support the migration of virtual machines across networks to achieve resource pooling. Cloudnet designs can be supported through optical networks [425]. Kantarci and Mouftah [384] have examined designs for a virtual cloud backbone network that interconnects distributed backbone nodes, whereby each backbone node is associated with one data center. A network resource manager periodically executes a virtualization algorithm to accommodate traffic demands through appropriate resource provisioning. Kantarci and Mouftah [384] have developed and evaluated algorithms for three provisioning objectives: minimize the outage probability of the cloud, minimize the resource provisioning, and minimize a tradeoff between resource saving and cloud outage probability. The range of performance characteristics for outage probability, resource consumption, and delays of the provisioning approaches have been evaluated through simulations. The outage probability of optical cloud networks has been reduced in [385] through optimized service re-locations.

Several complementary aspects of optical cloudnet networks have recently been investigated. A multilayer network architecture with an SDN based network management structure for cloud services has been developed in [386]. A dynamic variation of the sharing of optical network resources for intra- and inter-data center networking has been examined in [387]. The dynamic sharing does not statically assign optical network resources to virtual optical networks; instead, the network resources are dynamically assigned according to the time-varying traffic demands. An SDN based optical transport mode for data center traffic has been explored in [388]. Virtual machine migration mechanisms that take the characteristics of renewable energy into account have been examined in [389] while general energy efficiency mechanisms for optically networked could computing resources have been examined in [390].

2.5.3 Metro/Core Networks

2.5.3.1 Virtual Optical Network Embedding

Virtual optical network embedding seeks to map requests for virtual optical networks to a given physical optical network infrastructure (substrate). A virtual optical network consists of both a set of virtual nodes and a set of interconnecting links that need to be mapped to the network substrate. This mapping of virtual networks consisting of both network nodes and links is fundamentally different from the extensively studied virtual topology design for optical wavelength routed networks [426], which only considered network links (and did not map nodes). Virtual network embedding of both nodes and link has already been extensively studied in general network graphs [166, 427]. However, virtual optical network embedding requires additional constraints to account for the special optical transmission characteristics, such as the wavelength continuity constraint and the transmission reach constraint. Consequently, several studies have begun to examine virtual network embedding algorithms specifically for optical networks.

Impairment-Aware Embedding Peng et al. [391, 392] have modeled the optical transmission impairments to facilitate the embedding of isolated VONs in a given underlying physical network infrastructure. Specifically, they model the physical (photonic) layer impairments of both single-line rate and mixed-line rates [428]. Peng et al. [392]

consider intra-VON impairments from Amplified Spontaneous Emission (ASE) and inter-VON impairments from non-linear impairments and four wave mixing. These impairments are captured in a Q-factor [429, 430], which is considered in the mapping of virtual links to the underlying physical link resources, such as wavelengths and wavebands.

Embedding on WDM and Flexi-grid Networks Zhang et al. [393] have considered the embedding of overall virtual networks encompassing both virtual nodes and virtual links. Zhang et al. have considered both conventional WDM networks as well as flexi-grid networks. For each network type, they formulate the virtual node and virtual link mapping as a mixed integer linear program. Concluding that the mixed integer linear program is NP-hard, heuristic solution approaches are developed. Specifically, the overall embedding (mapping) problem is divided into a node mapping problem and a link mapping problem. The node mapping problem is heuristically solved through a greedy MinMapping strategy that maps the largest computing resource demand to the node with the minimum remaining computing capacity (a complementary MaxMapping strategy that maps the largest demand to the node with the maximum remaining capacity is also considered). After the node mapping, the link mapping problem is solved with an extended grooming graph [431]. Comparisons for a small network indicate that the MinMapping strategy approaches the optimal mixed integer linear program solution quite closely; whereas the MaxMapping strategy gives poor results. The evaluations also indicate that the flexi-grid network requires only about half the spectrum compared to an equivalent WDM network for several evaluation scenarios.

The embedding of virtual optical networks in the context of elastic flexi-grid optical networking has been further examined in several studies. For a flexi-grid network based on OFDM [122], Zhao et al. [394] have compared a greedy heuristic that maps requests in decreasing order of the required resources with an arbitrary first-fit benchmark. Gong et al. [395] have considered flexi-grid networks with a similar overall strategy of node mapping followed by link mapping as Zhang et al. [393]. Based on the local resource constraints at each node, Gong et al. have formed a layered auxiliary graph for the node mapping. The link mapping is then solved with a shortest path routing approach. Wang et al. [396] have examined an embedding approach based on candidate mapping patterns that could provide the requested resources. The VON is then embedded according to a shortest path routing. Pages et al. [382] have considered embeddings that minimize the required optical transponders.

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Survivable Embedding Survivability of a virtual optical network, i.e., its continued operation in the face of physical node or link failures, is important for many applications that require dependable service. Hu et al. [397] developed an embedding that can survive the failure of a single physical node. Ye et al. [398] have examined the embedding of virtual optical networks so as to survive the failure of a single physical node or a physical link. Specifically, Ye et al. ensure that each virtual node request is mapped to a primary physical node as well as a distinct backup physical node. Similarly, each virtual link is mapped to a primary physical route as well as a node-disjoint backup physical route. Ye et al. mathematically formulate an optimization problem for the survivable embedding and then propose a Parallel Virtual Infrastructure (VI) Mapping (PAR) algorithm. The PAR algorithm finds distinct candidate physical nodes (with the highest remaining resources) for each virtual node request. The candidate physical nodes are then jointly examined with pairs of shortest node-disjoint paths. The evaluations in [398] indicate that the parallel PAR algorithm reduces the blocking probabilities of virtual network requests by 5–20 % compared to a sequential algorithm benchmark. A limitation of the survivable embedding [398] is that it protects only from a single link or node failure. As the optical infrastructure is expected to penetrate deeper in the access network deployments (e.g., mobile back-haul), it will become necessary to consider multiple failure points. Similar survivable network embedding algorithms that employ node-disjoint shortest paths in conjunction with specific cost metrics for node mappings have been investigated by Xie et al. [399] and Chen et al. [400]. Jiang et al. [401] have examined a solution variant based on maximum-weight maximum clique formation.

The studies [402–404] have examined so-called bandwidth squeezed restoration for virtual topologies. With bandwidth squeezing, the back-up path bandwidths of the surviving virtual topologies are generally lower than the bandwidths on the working paths.

Survivable virtual topology design in the context of multidomain optical networks has been studied by Hong et al. [405]. Hong et al. focused on minimizing the total network link cost for a given virtual traffic demand. A heuristic algorithm for partition and contraction mechanisms based on cut set theory has been proposed for the mapping of virtual links onto multidomain optical networks. A hierarchical SDN control plane is split between local controllers that to manage individual domains and a global controller for the overall management. The partition and contraction mechanisms abstract inter- and intra-domain information as a method of contraction. Survivability conditions are ensured individually for inter- and intra-domains such that survivability is met for the entire network. The evaluations in [405] demonstrate successful virtual network mapping at the scale required by commercial Internet service providers and infrastructure providers.

Dynamic Embedding The embedding approaches surveyed so far have mainly focused on the offline embedding of a static set of virtual network requests. However, in the ongoing network operation the dynamic embedding of modifications (upgrades) of existing virtual networks, or the addition of new virtual networks are important. Ye et al. [406] have examined a variety of strategies for upgrading existing virtual topologies. Ye et al. have considered both scenarios without advance planning (knowledge) of virtual network upgrades and scenarios that plan ahead for possible (anticipated) upgrades. For both scenarios, a divide-and-conquer strategy and an integrate-and-cooperate strategy are examined. The divide-and conquer strategy sequentially maps all the virtual nodes and then the virtual links. In contrast, the integrate-and-cooperate strategy jointly considers the virtual node and virtual link mappings. Without advance planning, these strategies are applied sequentially, as the virtual network requests arrive over time, whereas, with planning, the initial and upgrade requests are jointly considered. Evaluation results indicate that the integrate-and-cooperate strategy slightly increases a revenue measure and request acceptance ratio compared to the divide-and-conquer strategy. The results also indicate that planning has the potential to substantially increase the revenue and acceptance ratio. In a related study, Zhang et al. [407] have examined embedding algorithms for virtual network requests that arrive dynamically to a multilayer network consisting of electrical and optical network substrates.

Energy-efficient Embedding Motivated by the growing importance of green networking and information technology [432], a few studies have begun to consider the energy efficiency of the embedded virtual optical networks. Nonde et al. [408] have developed and evaluated mechanisms for embedding virtual cloud networks so as to minimize the overall power consumption, i.e., the aggregate of the power consumption for communication and computing (in the data centers). Nonde et al. have incorporated the power consumption of the communication components, such as transponders and optical switches, as well as the power consumption characteristics of data center servers into a mathematical power minimization model. Nonde et al. then develop a real-time heuristic for energy-optimized virtual network embedding. The heuristic strives to consolidate computing requests in the physical nodes with the least residual computing capacity. This consolidation strategy is motivated by the typical power consumption characteristic of a compute server that has a significant idle power consumption and then grows linearly with increasing computing load; thus a fully loaded server is more energy-efficient than a lightly loaded server. The bandwidth demands are then routed between the nodes according to a minimum hop algorithm. The energy optimized embedding is compared with a cost optimized embedding that only seeks to minimize the number of utilized wavelength channels. The evaluation results in [408] indicate that the energy optimized embedding significantly reduces the overall energy consumption for low to moderate loads on the physical infrastructure; for high loads, when all physical resources need to be utilized, there are no significant savings. Across the entire load range, the energy optimized embedding saves on average 20 % energy compared to the benchmark minimizing the wavelength channels.

Chen [409] has examined a similar energy-efficient virtual optical network embedding that considers primary and link-disjoint backup paths, similar to the survivable embeddings in Section 2.5.3.1. More specifically, virtual link requests are mapped in decreasing order of their bandwidth requirements to the shortest physical transmission distance paths, i.e., the highest virtual bandwidth demands are allocated to the shortest physical paths. Evaluations indicate that this link mapping approach roughly halves the power consumption compared to a random node mapping benchmark. Further studies focused on energy savings have examined virtual link embeddings that maximize the usage of nodes with renewable energy [410] and the traffic grooming [411] onto sliceable BVTs [433].

2.5.3.2 Hypervisors for VONs

The operation of VONs over a given underlying physical (substrate) optical network requires an intermediate hypervisor. The hypervisor presents the physical network as multiple isolated VONs to the corresponding VON controllers (with typically one VON controller per VON). In turn, the hypervisor intercepts the control messages issued by a VON controller and controls the physical network to effect the control actions desired by the VON controller for the corresponding VON.

Towards the development of an optical network hypervisor, Siquera et al. [412] have developed a SDN-based controller for an optical transport architecture. The controller implements a virtualized GMPLS control plane with offloading to facilitate the implementation of hypervisor functionalities, namely the creation optical virtual private networks, optical network slicing, and optical interface management. A major contribution of Siquera et al. [412] is a Transport Network Operating System (T-NOS), which abstracts the physical layer for the controller and could be utilized for hypervisor functionalities.

OpenSlice [413] is a comprehensive OpenFlow-based hypervisor that creates VONs over underlying elastic optical networks [185, 186]. OpenSlice dynamically provisions end-to-end paths and offloads IP traffic by slicing the optical communications spectrum. The paths are set up through a handshake protocol that fills in cross-connection table entries. The control messages for slicing the optical communications spectrum, such as slot width and modulation format, are carried in extended OpenFlow protocol messages. OpenSlice relies on special distributed network elements, namely bandwidth variable wavelength cross-connects [434] and multiflow optical transponders [246] that have been extended for control through the extended OpenFlow messages. The OpenSlice evaluation includes an experimental demonstration. The evaluation results include path provisioning latency comparisons with a GMPLS-based control plane and indicate that OpenFlow outperforms GMPLS for paths with more than three hops. OpenSlice extension and refinements to multilayer and multidomain networks are surveyed in Section 2.7. An alternate centralized Optical FlowVisor that does not require extensions to the distributed network elements has been investigated in [414].

2.5.4 Virtualization: Summary and Discussion

The virtualization studies on access networks [12, 367, 368, 370–379] have primarily focused on exploiting and manipulating the specific properties of the optical physical layer (e.g., different OFDMA subcarriers) and MAC layer (e.g., polling based MAC protocol) of the optical access networks for virtualization. In addition, to virtualization studies on purely optical PON access networks, two sets of studies, namely sets [372–377] and WiMAX-VPON [378, 379] have examined virtualization for two forms of FiWi access networks. Future research needs to consider virtualization of a wider set of FiWi network technologies, i.e., FiWi networks that consider optical access networks with a wider variety of wireless access technologies, such as different forms of cellular access or combinations of cellular with other forms of wireless access. Also, virtualization of integrated access and metropolitan area networks [435–438] is an important future research direction.

A set of studies has begun to explore optical networking support for SDN-enabled cloudnets that exploit virtualization to dynamically pool resources across distributed data centers. One important direction for future work on cloudnets is to examine moving data center resources closer to the users and the subsequent resource

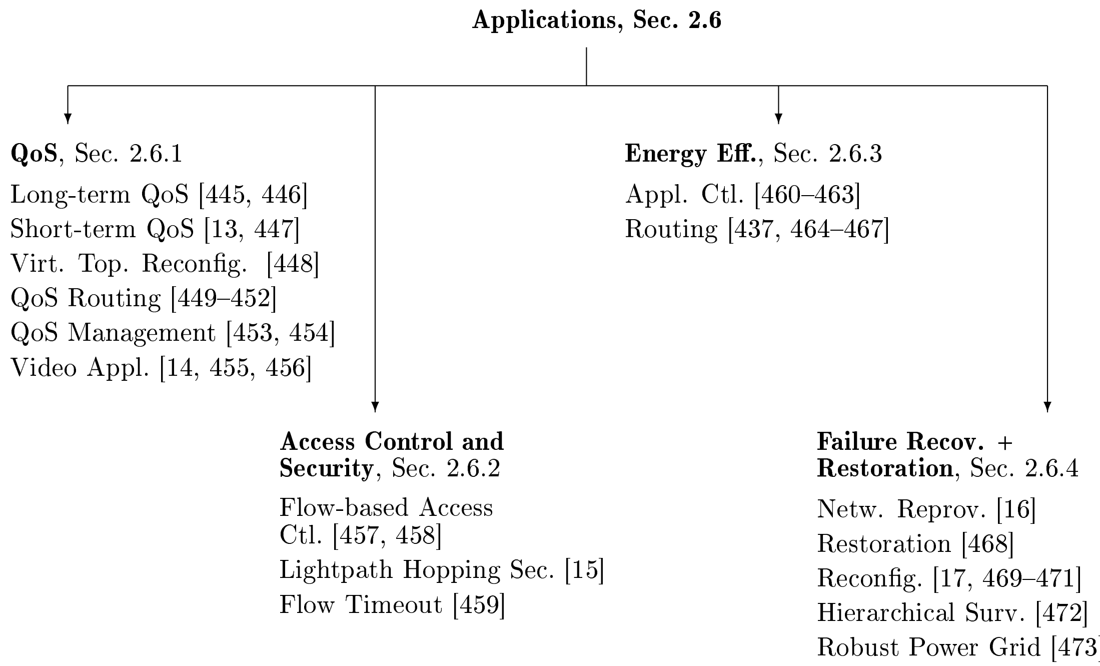


Figure 2.12: Classification of application layer SDON studies.

pooling across edge networks [439]. Also, the exploration of the benefits of FiWi networks for decentralized cloudlets [440–443] that support mobile wireless network services is an important future research direction [444].

A fairly extensive set of studies has examined virtual network embedding for metro/core networks. The virtual network embedding studies have considered the specific limitations and constraints of optical networks and have begun to explore specialized embedding strategies that strive to meet a specific optimization objective, such as survivability, dynamic adaptability, or energy efficiency. Future research should seek to develop a comprehensive framework of embedding algorithms that can be tuned with weights to achieve prescribed degrees of the different optimization objectives.

A relatively smaller set of studies has developed and refined hypervisors for creating VONs over metro/core optical networks. Much of the SDON hypervisor research has centered on the OpenSlice hypervisor concept [413]. While OpenSlice accounts for the specific characteristics of the optical transmission medium, it is relatively complex as it requires a distributed implementation with specialized optical networking components. Future research should seek to achieve the hypervisor functionalities with a wider set of common optical components so as to reduce cost and complexity. Overall, SDON hypervisor research should examine the performance-complexity/cost tradeoffs of distributed versus centralized approaches. Within this context of examining the spectrum of distributed to centralized hypervisors, future hypervisor research should further refine and optimize the virtualization mechanisms so as to achieve strict isolation between virtual network slices, as well as low-complexity hypervisor deployment, operation, and maintenance.

2.6 SDN APPLICATION LAYER

In the SDN paradigm, applications interact with the controllers to implement network services. We organize the survey of the studies on application layer aspects of SDONs according to the main application categories of quality of service (QoS), access control and security, energy efficiency, and failure recovery, as illustrated in Fig. 2.12.

2.6.1 QoS

2.6.1.1 Long-term QoS: Time-Aware SDN

Data Center (DC) networks move data back and forth between DCs to balance the computing load and the data storage usage (for upload) [474]. These data movements between DCs can span large geographical areas and help ensure DC service QoS for the end users. Load balancing algorithms can exploit the characteristics of the user requests. One such request characteristic is the high degree of time-correlation over various time scales ranging from several hours of a day (e.g., due to a sporting event) to several days in a year (e.g., due to a political event). Zhao et al. [445] have proposed a time-aware SDN application using OpenFlow extensions to dynamically balance the

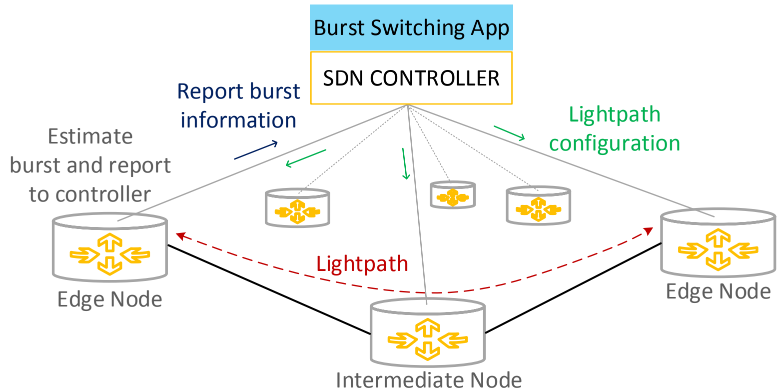


Figure 2.13: Optical SDN-based QoS-aware burst switching application [13].

load across the DC resources so as to improve the QoS. Specifically, a time correlated PCE algorithm based on flexi-grid optical transport (see Section 2.4.4.2) has been proposed. An SDN application monitors the DC resources and applies network rules to preserve the QoS. Evaluations of the algorithm indicate improvements in terms of network blocking probability, global blocking probability, and spectrum consumption ratio. This study did not consider short time scale traffic bursts, which can significantly affect the load conditions.

We believe that in order to avoid pitfalls in the operation of load balancing through PCE algorithms implemented with SDN, a wide range of traffic conditions needs to be considered. The considered traffic range should include short and long term traffic variations, which should be traded off with various QoS aspects, such as type of application and delay constraints, as well as the resulting costs and control overheads. Khodakarami et al. [446] have taken steps in this direction by forming a traffic forecasting model for both long-term and short-term forecasts in a wide-area mesh network. Optical lightpaths are then configured based on the overall traffic forecast, while electronic switching capacities are allocated based on short-term forecasts.

2.6.1.2 Short Term QoS

Users of a high-speed FTTH access network may request very large bandwidths due to simultaneously running applications that require high data rates. In such a scenario, applications requiring very high data rates may affect each other. For instance, a video conference running simultaneously with the streaming of a sports video may result in call drops in the video conference application and in stalls of the sports video. Li et al. [447] proposed an SDN based bandwidth provisioning application in the broadband remote access server [475] network. They defined and assigned the minimum bandwidth, which they named "sweet point", required for each application to experience good QoE. Li et al. showed that maintaining the "sweet point" bandwidth for each application can significantly improve the QoE while other applications are being served according to their bandwidth requirements.

In a similar study, Patel et al. [13] proposed a burst switching mechanism based on a software defined optical network. Bursts typically originate at the edge nodes and the aggregation points due to statistical multiplexing of high speed optical transmissions. To ensure QoS for multiple traffic classes, bursts at the edge nodes have to be managed by deciding their end-to-end path to meet their QoS requirements, such as minimum delay and data rate. In non-SDN based mechanisms, complicated distributed protocols, such as GMPLS [363, 365], are used to route the burst traffic. In the proposed application, the centralized unified control plane decides the routing path for the burst based on latency and QoS requirements. A simplified procedure involves (*i*) burst evaluation at the edge node, (*ii*) reporting burst information to the SDN controller, and (*iii*) sending of configurations to the optical nodes by the controller to set up a lightpath as illustrated in Fig. 2.13. Simulations indicate an increase of performance in terms of throughput, network blocking probability, and latency along with improved QoS when compared to non-SDN GMPLS methods.

2.6.1.3 Virtual Topology Reconfigurations

The QoS experienced by traffic flows greatly depends on their route through a network. Wette et al. [448] have examined an application algorithm that reconfigures WDM network virtual topologies (see Section 2.5.3.1) according to the traffic levels. The algorithm considers the localized traffic information and optical resource availability at the nodes. The algorithm does not require synchronization, thus reducing the overhead while simplifying the network design. In the proposed architecture, optical switches are connected to ROADMs. The reconfiguration application manages and controls the optical switches through the SDN controller. A new WDM controller is introduced to configure the lightpaths taking wavelength conversion and lightpath switching at the ROADMs into consideration. The SDN controller operates on the optical network which appears as a static network, while the WDM controller configures (and re-configures) the ROADMs to create multiple virtual optical networks according to the traffic levels. Evaluation results indicate improved utilization and throughput. The results indicate that virtual topologies reconfigurations can significantly increase the flexibility of the network while achieving the desired QoS. However, the control overhead and the delay aspects due to virtualization and separation of control and lightwave paths needs to be carefully considered.

2.6.1.4 End-to-End QoS Routing

Interconnections between DCs involve typically multiple data paths. All the interfaces existing between DCs can be utilized by MultiPath TCP (MPTCP). Ensuring QoS in such an MPTCP setting while preserving throughput efficiency in a reconfigurable underlying burst switching optical network is a challenging task. Tariq et al. [449] have proposed QoS-aware bandwidth reservation for MPTCP in an SDON. The bandwidth

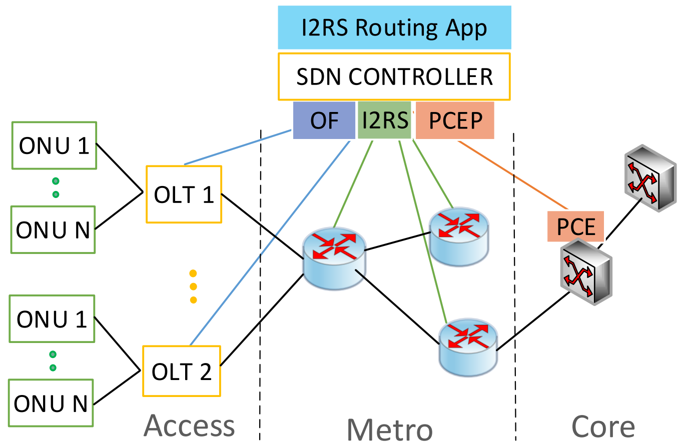


Figure 2.14: Illustration of routing application.

reservation proceeds in two stages (*i*) path selection for MPTCP, and (*ii*) OBS wavelength reservation to assign the priorities for latency-sensitive flows. Larger portions of a wavelength reservation are assigned to high priority flows, resulting in reduced burst blocking probability while achieving the higher MPTCP throughput. The simulation results in [449] validate the two-stage algorithm for QoS-aware MPTCP over an SDON, indicating decreased dropping probabilities, and increased throughputs.

Information To the Routing System (I2RS) [476] is a high-level architecture for communicating and interacting with routing systems, such as BGP routers. A routing system may consists of several complex functional entities, such as a Routing Information Base (RIB), an RIB manager, topology and policy databases, along with routing and signalling units. The I2RS provides a programmability platform that enables access and modifications of the configurations of the routing system elements. The I2RS can be extended with SDN principles to achieve global network management and reconfiguration [477]. Sgambelluri et al. [450] presented an SDN based routing application within the I2RS framework to integrate the control of the access, metro, and core networks as illustrated in Fig. 2.14. The SDN controller communicates with the Path Computation Elements (PCEs) of the core network to create Label

Switched Paths (LSPs) based on the information received by the OLTs. Experimental demonstrations validated the routing optimization based on the current traffic status and previous load as well as the unified control interface for access, metro, and core networks.

Ilchmann et al. [451] developed an SDN application that communicates to an SDN controller via an HTTP-based REST API. Over time, lightpaths in an optical network can become inefficient for a number of reasons (e.g., optical spectrum fragmentation). For this reason, Ilchmann et al. developed an SDN application that evaluates existing lightpaths in an optical network and offers an application user the option to re-optimize the lightpath routing to improve various performance metrics (e.g., path length). The application is user-interactive in that the user can see the number of proposed lightpath routing changes before they are made and can potentially select a subset of the proposed changes to minimize network down-time.

At the ingress and egress routers of optical networks (e.g., the edge routers between access and metro networks), buffers are highly non-economical to implement, as they require large buffers sizes to accommodate the channel rates of 40 Mb/s or more. To reduce the buffer requirements at the edge routers, Chang et al. [452] have proposed a backpressure application referred to as Refill and SDN-based Random Early Detection (RS-RED). RS-RED implements a refill queue at the ingress device and a droptail queue at the egress device, whereby both queues are centrally managed by the RS-RED algorithm running on the SDN controller. Simulation results showed that at the expense of small delay increases, edge router buffer sizes can be significantly reduced.

2.6.1.5 QoS Management

Rukert et al. [453] proposed SDN based controlled home-gateway supporting heterogeneous wired technologies, such as DSL, and wireless technologies, such as LTE and WiFi. SDN controllers managed by the ISPs optimize the traffic flows to each user while accommodating large numbers of users and ensuring their minimum QoS. Additionally, Tego et al. [454] demonstrated an experimental SDN based QoS management setup to optimize the energy utilization. GbE links are switched on and off based on the traffic levels. The QoS management reroutes the traffic to avoid congestion and achieve efficient throughput. SDN applications conduct active QoS probing to monitor the network QoS characteristics. Evaluations have indicated that the SDN based techniques achieve significantly higher throughput than non-SDN techniques [454].

2.6.1.6 Video Applications

The application-aware SDN-enabled resource allocation application has been introduced by Chitimalla et al. [455] to improve the video QoE in a PON access network. The resource allocation application uses application level feedback to schedule the optical resources. The video resolution is incrementally increased or decreased based on the buffer utilization statistics that the client sends to the controller. The scheduler at the OLT schedules the packets based on weights calculated by the SDN controller, whereby the video applications at the clients communicate with the controller to determine the weights. If the network is congested, then the SDN controller communicates to the clients to reduce the video resolution so as to reduce the stalls and to improve the QoE.

Caching of video data close the users is generally beneficial for improving the QoE of video services [478, 479]. Li et al. [14] have introduced caching mechanisms

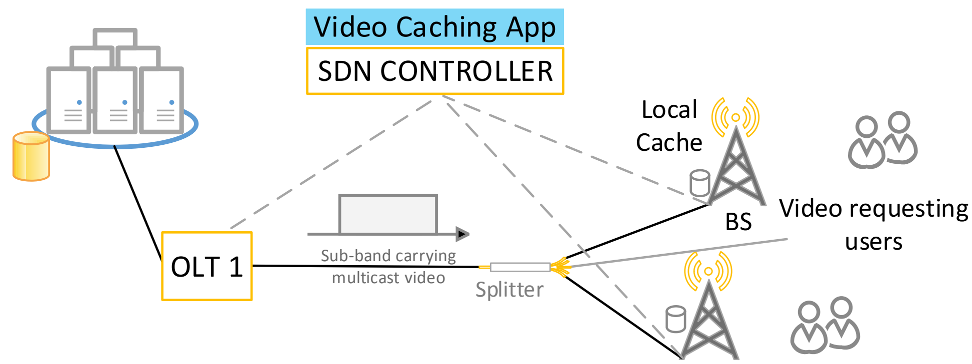


Figure 2.15: SDN based video caching application in PON for mobile users [14].

for software-defined PONs. In particular, Li et al. have proposed joint provisioning of the bandwidth to service the video and the cache management, as illustrated in Fig. 2.15. Based on the request frequency for specific video content, the Base Station (BS) caches the content with the assistance of the SDN controller. The proposed *push*-based mechanism delivers (pushes) the video to the BS caches when the PON is not congested. A specific PON transmission sub-band can be used to multicast video content that needs to be cached at multiple BSs. The simulation evaluation in [14] indicate that up to 30% additional videos can be serviced while the service response delay is reduced to 50%.

2.6.2 Access Control and Security

2.6.2.1 Flow-based Access Control

Network Access Control (NAC) is a networking application that regulates the access to network services [342, 480]. A NAC based on traffic flows has been developed by Matias [457]. Flow-NAC exploits the forwarding rules of OpenFlow switches, which are set by a central SDN controller, to control the access of traffic flows to network services. FlowNAC can implement the access control based on various flow identifiers, such as MAC addresses or IP source and destination addresses. Performance evaluations measured the connections times for flows on a testbed and found average

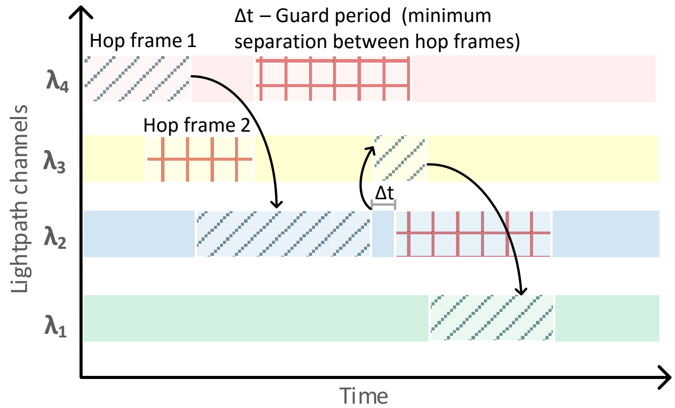


Figure 2.16: Overview of optical light path hopping mechanism [15].

connection times on the order of 100 ms for completing the flow access control.

In a related study, Nayak et al. [458] developed the Resonance flow based access control system for an enterprise network. In the Resonance system, the network elements, such as the routers themselves, dynamically enforce access control policies. The access control policies are implemented through real-time alerts and flow based information that is exchanged with SDN principles. Nayak et al. have demonstrated the Resonance system on a production network at Georgia Tech. The Resonance design can be readily implemented in SDON networks and can be readily extended to wide area networks. Consider for example multiple heterogeneous DCs of multiple organizations that are connected by an optical backbone network. The Resonance system can be extended to provide access control mechanisms, such as authentication and authorization, through such a wide area SDON.

2.6.2.2 Lightpath Hopping Security

The broad network perspective of SDN controllers facilitates the implementation of security functions that require this broad perspective [119, 120, 481]. However, SDN may also be vulnerable to a wide range of attacks and vulnerabilities, including unauthorized access, data leakage, data modification, and misconfiguration. Eavesdropping and jamming are security threats on the physical layer and are especially relevant for the optical layer of SDONs. In order to prevent eavesdropping and jamming in an optical lightpath, Li et al. [15] have proposed an SDN based fast lightpath hopping mechanism. As illustrated in Fig. 2.16, the hopping mechanism operates over multiple lightpath channels. Conventional optical lightpath setup times range from several hundreds of milliseconds to several seconds and would result in a very low hopping frequency. To avoid the optical setup times during each hopping period, an SDN based high precision time synchronization has been proposed. As a result, a fast hopping mechanism can be implemented and executed in a coordinated manner. A hop frame is defined and guard periods are added in between hop frames. The experimental evaluations indicate that a maximum hopping frequency of 1 MHz can be achieved with a BER of 1×10^{-3}. However, shortcomings of such mechanisms are the secure exchange of hopping sequences between the transmitter and the receiver. Although, centralized SDN control provides authenticated provisioning of the hopping sequence, additional mechanisms to secure the hopping sequence from being obtained through man-in-the-middle attacks should be investigated.

2.6.2.3 Flow Timeout

SDN flow actions on the forwarding and switching elements have generally a validity period. Upon expiration of the validity period, i.e., the flow action timeout, the forwarding or switching element drops the flow action from the forwarding information base or the flow table. The switching element CPU must be able to access the flow action information with very low latency so as to perform switching actions at the line rate. Therefore, the flow actions are commonly stored in Ternary Content Addressable Memories (TCAMs) [482], which are limited to storing on the order of thousands of distinct entries. In SDONs, the optical network elements perform the actions set by the SDN controller. These actions have to be stored in a finite memory space.

Therefore, it is important to utilize the finite memory space as efficiently as possible [483–487]. In the dynamic timeout approach [459], the SDN controller tracks the TCAM occupancy levels in the switches and adjusts timeout durations accordingly. However, a shortcoming of such techniques is that the bookkeeping processes at the SDN controllers can become cumbersome for a large network. Therefore, autonomous timeout management techniques that are implemented at the hypervisors can reduce the controller processing load and are an important future research direction.

2.6.3 Energy Efficiency

The separation of the control plane from the data plane and the global network perspective are unique advantages of SDN for improving the energy efficiency of networks, which is an important goal [488, 489].

2.6.3.1 Power-saving Application Controller

Ji et al. [460] have proposed an all optical energy-efficient network centered around an application controller [461, 462] that monitors power consumption characteristics and enforces power savings policies. Ji et al. first introduce energy-efficient variations of Digital-to-Analog Converters (DACs) and wavelength selective ROADMs as components for their energy-efficient network. Second, Jie et al. introduce an energy-efficient switch architecture that consists of multiple parallel switching planes, whereby each plane consists of three stages with optical burst switching employed in the second (central) switching stage. Third, Jie et al. detail a multilevel SDN based control architecture for the network built from the introduced components and switch. The control structure accommodates multiple networks domains, whereby each network domain can involve multiple switching technologies, such as time-based and frequency-based optical switching. All controllers for the various domains and technologies are placed under the control of an application controller. Dedicated power monitors that are distributed throughout the network update the SDN based application controller about the energy consumption characteristics of each network node. Based on the received energy consumption updates, the application controller executes power-saving strategies. The resulting control actions are signalled by the application controller to the various controllers for the different network domains and technologies. An extension of this multi-level architecture to cloud-based radio access networks has been examined in [463].

2.6.3.2 Energy-Saving Routing

Tego et al. [464] have proposed an energy-saving application that switches off under-utilized GbE network links. Specifically, Tego et al. proposed two methods: Fixed Upper Fixed Lower (FUFL) and Dynamic Upper and Fixed Lower (DLFU). In FUFL, the IP routing and the connectivity of the logical topology are *fixed*. The utilization of physical GbE links (whereby multiple parallel physical links form a logical link) is compared with a threshold to determine whether to switch off or on individual physical links (that support a given logical link). The traffic on a physical link that is about to be switched off is rerouted on a parallel physical GbE link (within the same logical link). In contrast, in the DLFU approach, the energy saving application monitors the load levels on the virtual links. If the load level on a given virtual link falls below a threshold value, then the virtual link topology is reconfigured to eliminate the virtual link with the low load. A general pitfall of such link switch-off techniques is that energy savings may be achieved at the expense of deteriorating QoS. The QoS should therefore be closely monitored when switching off links and re-routing flows.

A similar SDN based routing strategy that strives to save energy while preserving the QoS has been examined in the context of a GMPLS optical networks

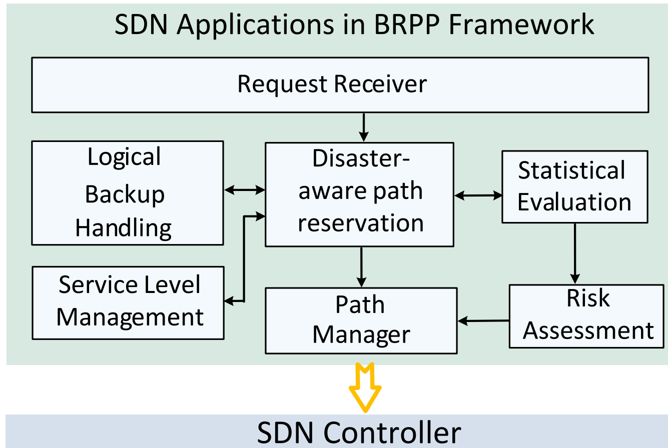


Figure 2.17: Illustration of application layer for disaster aware networking [16].

in [465]. Multipath routing optimizing applications that strive to save energy in an SDN based transport optical network have been presented in [466]. A similar SDN based optimization approach for reducing the energy consumption in data centers has been examined by Yoon et al. [467]. Yoon et al. formulated a mixed integer linear program that models the switches and hosts as queues. Essentially, the optimization decides on the switches and hosts that could be turned off. As the problem is NP-hard, annealing algorithms are examined. Simulations indicate that energy savings of more than 80% are possible for low data center utilization rates, while the energy savings decrease to less than 40% for high data center utilization rates. Traffic balancing in the metro optical access networks through the SDN based reconfiguration of optical subscriber units in a TWDM-PON systems for energy savings has been additionally demonstrated in [437].

2.6.4 Failure Recovery and Restoration

2.6.4.1 Network Reprovisioning

Network disruptions can occur due to various natural and/or man-made factors. Network resource reprovisioning is a process to change the network configurations, e.g., the network topology and routes, to recover from failures. A Backup Reprovisioning with Path Protection (BRPP), based on SDN for optical networks has been presented by Savas et al. [16]. An SDN application framework as illustrated in Fig. 2.17 was designed to support the reprovisioning with services, such as provisioning the new connections, risk assessment, as well as service level and backup management. When new requests are received by the BRPP application framework, the statistics module evaluates the network state to find the primary path and a link-disjoint backup path. The computed backup paths are stored as logical links without being provisioned on the physical network. The logical backup module manages and recalculates the logical links when a new backup path cannot be accommodated or to optimize the existing backup paths (e.g., minimize the backup path distance). Savas et al. introduce a degraded backup path mechanism that reserves not the full, but a lower (degraded) transmission capacity on the backup paths, so as to accommodate more requests. Emulations of the proposed mechanisms indicate improved network utilization while effectively provisioning the backup paths for restoring the network after network failures.

As a part of DARPA's core optical networks CORONET project, a non-SDN based Robust Optical Layer End-to-end X-connection (ROLEX) protocol has been demonstrated and presented along with the lessons learned [490]. ROLEX is a distributed protocol for failure recovery which requires a considerable amount of signaling between nodes for the distributed management. Therefore to avoid the pitfall of excessive signalling, it may be worthwhile to examine a ROLEX version with centralized SDN control in future research to reduce the recovery time and signaling overhead, as well as the costs of restored paths while ensuring the user QoS.

2.6.4.2 Restoration Processing

During a restoration, the network control plane simultaneously triggers backup provisioning of all disrupted paths. In GMPLS restoration, along with signal flooding, there can be contention of signal messages at the network nodes. Contentions may arise due to spectrum conflicts of the lightpath, or node-configuration overrides, i.e., a new configuration request arrives while a preceding reconfiguration is under way. Giorgetti et al. [468] have proposed dynamic restoration in the elastic optical network to avoid signaling contention in SDN (i.e., of OpenFlow messages). Two SDN restoration mechanisms were presented: (*i*) the independent restoration scheme (SDN-ind), and (*ii*) the bundle restoration scheme (SDN-bund). In SDN-ind, the controller triggers simultaneous independent flow modification (Flow-Mod) messages for each backup path to the switches involved in the reconfigurations. During contention, switches enqueue the multiple received Flow-Mod messages and process them sequentially. Although SDN-ind achieves reduced recovery time as compared to non-SDN GMPLS, the waiting of messages in the queue incurs a delay. In SDN-bund, the backup path reconfigurations are bundled into a single message, i.e., a Bundle Flow-Mod message, and sent to each involved switch. Each switch then configures the flow modifications in one reconfiguration, eliminating the delay incurred by the queuing of Flow-Mod messages. A similar OpenFlow enabled restoration in Elastic Optical Networks (EONs) has been studied in [491].

2.6.4.3 Reconfiguration

Aguado et al. [17] have demonstrated a failure recovery mechanism as part of the EU FP7 STRAUSS project with dynamic virtual reconfigurations using SDN. They considered multidomain hypervisors and domain-specific controllers to virtualize the multidomain networks. The Application-Based Network Operations (ABNO) framework

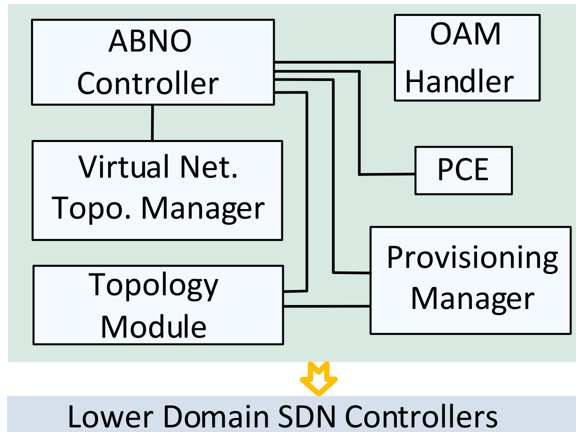


Figure 2.18: Illustration of Application-Based Network Operation (ABNO) architecture [17].

illustrated in Fig. 2.18 enables network automation and programmability. ABNO can compute end-to-end optical paths and delegate the configurations to lower layer domain SDN controllers. Requirements for fast recovery from network failures would be in the order of tens of milliseconds, which is challenging to achieve in large scale networks. ABNO reduces the recovery times by pre-computing the backup connections after the first failure, while the Operation, Administration and Maintenance (OAM) module [492] communicates with the ABNO controller to configure the new end-to-end connections in response to a failure alarm. Failure alarms are triggered by the domain SDN controllers monitoring the traffic via the optical power meters when power is below -20 dBm. In order to ensure survivability, an adaptive survivability scheme that takes routing as well as spectrum assignment and modulation into consideration has been explored in [469].

A similar design for end-to-end protection and failure recovery has been demonstrated by Slyne et al. [470] for a long-reach (LR) PON. LR-PON failures are highly likely due to physical breaks in the long feeder fibers. Along with the high impact of connectivity break down or degraded service, physical restoration time can be very long. Therefore, 1:1 protection for LR-PONs based on SDN has been proposed, where primary and secondary (backup) OLTs are used without traffic duplication. More specifically, Slyne et al. have devised and demonstrated an OpenFlow-Relay located at the switching unit. The OpenFlow-Relay detects and reports a failure along with fast updating of forwarding rules. Experimental demonstration show the backup OLT carrying protected traffic within 7.2 ms after a failure event.

An experimental demonstration utilizing multiple paths in optical transport networks for failure recovery has been discussed by Kim et al. [471]. Kim et al. have used commercial grade IP WDM network equipment and implemented multipath TCP in an SDN framework to emulate inter-DC communication. They developed an SDN application, consisting of an cross-layer service manager module and a cross-layer multipath transport module to reconfigure the optical paths for the recovery from connection impairments. Their evaluations show increased bandwidth utilization and reduced cost while being resilient to network impairments as the cross-layer multipath transport module does not reserve the backup path on the transport network.

2.6.4.4 Hierarchical Survivability

Networks can be made survivable by introducing resource redundancy. However, the cost of the network increases with increased redundancy. Zhang et al. [472] have demonstrated a highly survivable IP-Optical multilayered transport network. Hierarchal controllers are placed for multilayer resource provisioning. Optical nodes are controlled by Transport Controllers (TCs), while higher layers (IP) are controlled by unified controllers (UCs). The UCs communicate with the TCs to optimize the routes based on cross-layer information. If a fiber causes a service disruption, TCs may directly set up alternate routes or ask the UCs for optimized routes. A pitfall of such hierarchical control techniques can be long restoration times. However, the cross layer restorations can recover from high degrees of failures, such as multipoint and concurrent failures.

2.6.4.5 Robust Power Grid

The lack of a reliable communication infrastructure for power grid management was one the many reasons for the widespread blackout in the Northeastern U.S.A. in the year 2003, which affected the lives of 50 million people [493]. Since then building a reliable communication infrastructure for the power grid has become an important priority. Rastegarfar et al. [473] have proposed a communication infrastructure that is focused on monitoring and can react to and recover from failures so as to reliably support power grid applications. More specifically, their architecture was built on SDN based optical networking for implementing robust power grid control applications. Control and infrastructure in the SDN based power grid management exhibits an interdependency i.e., the physical fiber relies on the control plane for its operations and the logical control plane relies on the same physical fiber for its signalling communications. Therefore, they only focus on optical protection switching instead of IP layer protection, for the resilience of the SDN control. Cascaded failure mechanisms were modeled and simulated for two geographical topologies (U.S. and E.U.). In addition, the impacts of cascaded failures were studied for two scenarios (*i*) static optical layer (static OL), and (*ii*) dynamic optical layer (dynamic OL). Results for a static OL illustrated that the failure cascades are persistent and are closely dependent on the network topology. However, for a dynamic OL (i.e., with reconfiguration of the physical layer), failure cascades were suppressed by an average of 73%.

2.6.5 Application Layer: Summary and Discussion

The SDON QoS application studies have mainly examined traffic and network management mechanisms that are supported through the OpenFlow protocol and the

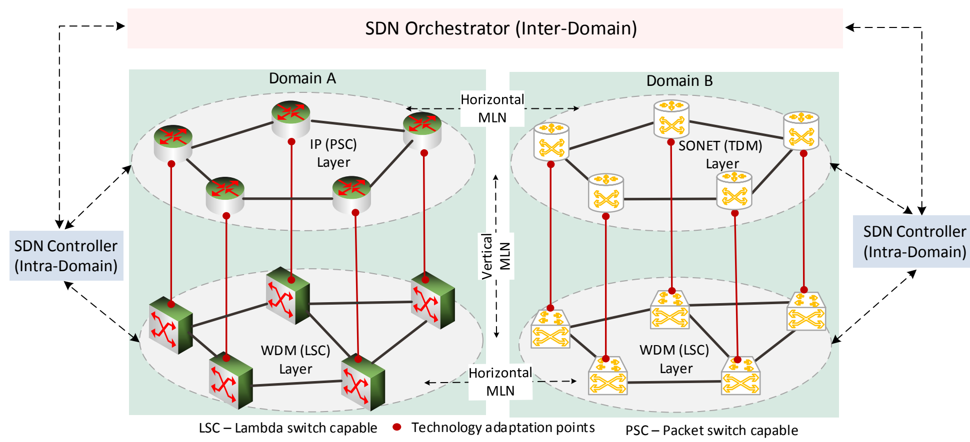


Figure 2.19: Illustration of SDN orchestration of multilayer networking.

central SDN controller. The studied SDON QoS applications are structurally very similar in that the traffic conditions or network states (e.g., congestion levels) are probed or monitored by the central SDN controller. The centralized knowledge of the traffic and network is then utilized to allocate or configure resources, such as DC resources in [445], application bandwidths in [447], and topology configurations or routes in [448–450, 452]. Future research on SDON QoS needs to further optimize the interactions of the controller with the network applications and data plane to quickly and correctly react to changing user demands and network conditions, so as to assure consistent QoS. The specific characteristics and requirements of video streaming applications have been considered in the few studies on video QoS [14, 455, 456]. Future SDON QoS research should consider a wider range of specific prominent application traffic types with specific characteristics and requirements, e.g., Voice over IP (VoIP) traffic has relatively low bit rate requirements, but requires low end-to-end latency.

Very few studies have considered security and access control for SDONs. The thorough study of the broad topic area of security and privacy is an important future research direction in SDONs, as outlined in Section 2.8.3 Energy efficiency is similarly a highly important topic within the SDON research area that has received relatively little attention so far and presents overarching research challenges, see Section 2.8.9.

One common theme of the SDON application layer studies focused on failure recovery and restoration has been to exploit the global perspective of the SDN control. The global perspective has been exploited for for improved planning of the recovery and restoration [16, 17, 472] as well as for improved coordination of the execution of the restoration processes [468, 491]. Generally, the existing failure recovery and restoration studies have focused on network (routing) domain that is owned by a particular organizational entity. Future research should seek to examine the tradeoffs when exploiting the global perspective of orchestration of multiple routing domains, i.e., the failure recovery and restoration techniques surveyed in this section could be combined with the multidomain orchestration techniques surveyed in Section 2.7. One concrete example of multidomain orchestration could be to coordinate the specific LR-PON access network protection and failure recovery [470] with protection and recovery techniques for metropolitan and core network domains, e.g., [16, 17, 471, 472], for improved end-to-end protection and recovery.

2.7 ORCHESTRATION

As introduced in Section 2.2.1.4, orchestration accomplishes higher layer abstract coordination of network services and operations. In the context of SDONs, orchestration has mainly been studied in support of multilayer networking. Multilayer networking in the context of SDN and network virtualization generally refers to networking across multiple network layers and their respective technologies, such as IP, MPLS, and WDM, in combination with networking across multiple routing domains [168, 494–497]. The concept of multilayer networking is generally an abstraction of providing network services with multiple networking layers (technologies) and multiple routing domains. The different network layers and their technologies are sometimes classified into Layer 0 (e.g., fiber-switch capable), Layer 1 (e.g., lambda switching capable), Layer 1.5 (e.g., TDM SONET/SDH), Layer 2 (e.g., Ethernet), Layer 2.5 (e.g., packet switching capable using MPLS), and Layer 3 (e.g., packet switching capable using IP routing) [498]. Routing domains are also commonly referred to as network domains, routing areas, or levels [494].

The recent multilayer networking review article [494] has introduced a range of capability planes to represent the grouping of related functionalities for a given networking technology. The capability planes include the data plane for transmitting and switching data. The control plane and the management plane directly interact with the data plane for controlling and provisioning data plane services as well as for trouble shooting and monitoring the data plane. Furthermore, an authentication and authorization plane, a service plane, and an application plane have been introduced for providing network services to users.

Multilayer networking can involve vertical layering or horizontal layering [494], as illustrated in Fig. 2.19. In vertical layering, a given layer, e.g., the routing layer, which may employ a particular technology, e.g., the Internet Protocol (IP), uses another (underlying) layer, e.g., the Wavelength Division Multiplexing (WDM) circuit switching layer, to provide services to higher layers. In horizontal layering, services are provided by "stitching" together a service path across multiple routing domains.

SDN provides a convenient control framework for these flexible multilayer networks [494]. Several research networks, such as ESnet, Internet2, GEANT, Science DMZ (Demilitarized Zone) have experimented with these multilayer networking concepts [499, 500]. In particular, SDN based multilayer network architectures, e.g., [438, 501, 502], are formed by conjoining the layered technology regions (*i*) in vertical fashion i.e., multiple technology layers internetwork within a single domain,

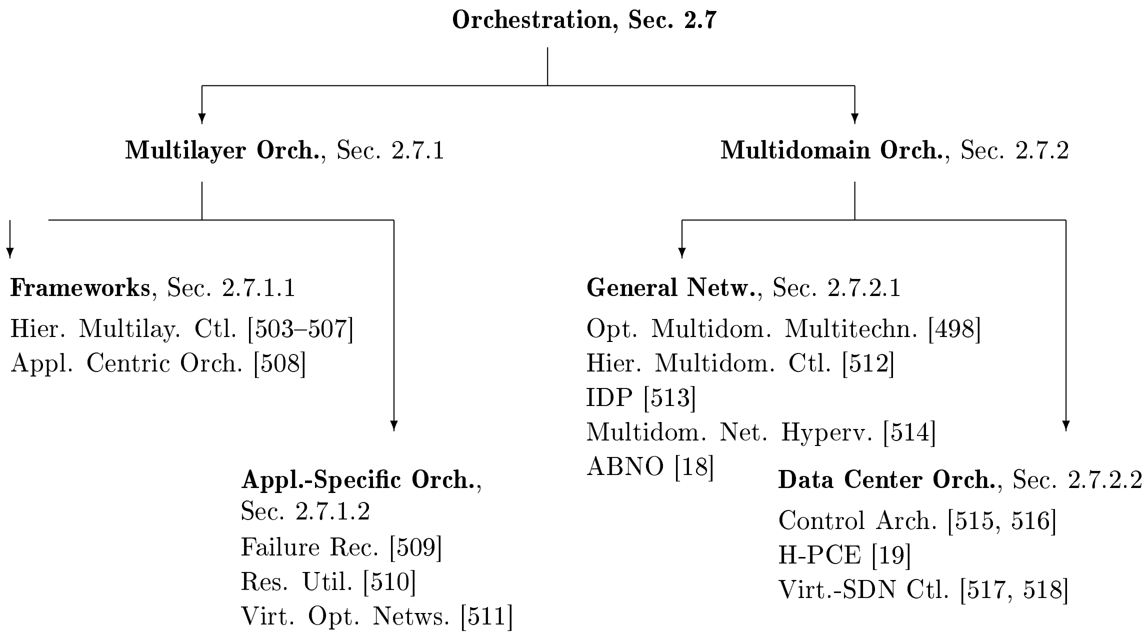


Figure 2.20: Classification of SDON orchestration studies.

or (*ii*) in horizontal layering fashion across multiple domains, i.e., technology layers internetwork across distinct domains. Horizontal multilayer networking can be viewed as a generalization of vertical multilayer networking in that the horizontal networking may involve the same or different (or even multiple) layers in the distinct domains. As illustrated in Fig. 2.19, the formed SDN based multilayer network architecture is controlled by an SDN orchestrator. As illustrated in Fig. 2.20 we organize the SDON orchestration studies according to their focus into studies that primarily address the orchestration of vertical multilayer (multitechnology) networking, i.e., the vertical networking across multiple layers (that typically implement different technologies) within a given domain, and into studies that primarily address the orchestration of horizontal multilayer (multidomain) networking, i.e., the horizontal networking across multiple routing domains (which may possibly involve different or multiple vertical layers in the different domains). We subclassify the vertical multilayer studies into general (vertical) multilayer networking frameworks and studies focused on supporting specific applications through vertical multilayer networking. We subclassify the multidomain (horizontal multilayer) networking studies into studies on general network domains and studies focused on internetworking with Data Center (DC) network domains.

2.7.1 Multilayer Orchestration

2.7.1.1 Multilayer Orchestration Frameworks

Hierarchical Multilayer Control Felix et al. [503] presented an hierarchical SDN control mechanism for packet optical networks. Multilayer optimization techniques are employed at the SDN orchestrator to integrate the optical transport technology with packet services by provisioning end-to-end Ethernet services. Two aspects are investigated, namely (*i*) bandwidth optimization for the optical transport services, and (*ii*) congestion control for packet network services in an integrated packet optical network. More specifically, the SDN controller initially allocates the minimum available bandwidth required for the services and then dynamically scales allocations based on the availability. Optical-Virtual Private Networks (O-VPNs) are created over the physical transport network. Services are then mapped to O-VPNs based on class of service requirements. When congestion is detected for a service, the SDN controller switches the service to another O-VPN, thus balancing the traffic to maintain the required class of service.

Similar steps towards the orchestration of multilayer networks have been taken within the OFELIA project [504–506]. Specifically, Shirazipour et al. [507] have explored extensions to OpenFlow version 1.1 actions to enable multitechnology transport layers, including Ethernet transport and optical transport. The explorations of the extensions include justifications of the use of SDN in circuit-based transport networks.

Application Centric Orchestration Gerstel et al. [508] proposed an application centric network service provisioning approach based on multilayer orchestration. This approach enables the network applications to directly interact with the physical layer resource allocations to achieve the desired service requirements. Application requirements for a network service may include maximum end-to-end latency, connection setup and hold times, failure protection, as well as security and encryption. In traditional IP networking, packets from multiple applications requiring heterogeneous services are simply aggregated and sent over a common transport link (IP services). As a result, network applications are typically assigned to a single (common) transport service within an optical link. Consider a failure recovery process with multiple available paths. IP networking typically selects the single path with the least end-to-end delay. However, some applications may tolerate higher latencies and therefore, the traffic can be split over multiple restoration paths achieving better traffic management. The orchestrator needs to interact with multiple network controllers operating across multiple (vertical) layers supported by north/south bound interfaces to achieve the application centric control. Dynamic additions of new IP links are demonstrated to accommodate the requirements of multiple application services with multiple IP links when the load on the existing IP link was increased.

2.7.1.2 Application-specific Orchestration

Failure Recovery Generally, network CapEx and OpEx increase as more protection against network failures is added. Khaddam et al. [509] propose an SDN based integration of multiple layers, such as WDM and IP, in a failure recovery mechanism to improve the utilization (i.e., to eventually reduce CapEx and OpEx while maintaining high protection levels). An observation study was conducted over a five year period to understand the impact of network failures on the real deployment of backbone networks. Results showed 75 distinct failures following a Pareto distribution, in which, 48% of the total deployed capacity was affected by the top (i.e., the highest impact) 20% of the failures. And, 10% of the total deployed capacity was impacted by the top two failure instances. These results emphasize the significance of backup capacities in the optical links for restoration processes. However, attaining the optimal protection capacities while achieving a high utilization of the optical links is challenging. A failure recovery mechanism is proposed based on a "hybrid" (i.e., combination of optical transport and IP) multilayer optimization. The hybrid mechanism improved the optical link utilization up to 50 %. Specifically, 30 % increase of the transport capacity utilization is achieved by dynamically reusing the remainder capacities in the optical links, i.e., the capacity reserved for failure recoveries. The multilayer optimization technique was validated on an experimental testbed utilizing central path-computation (PCE) [160] within the SDN framework. Experimental verification of failure recovery mechanism resulted in recovery times on the order of sub-seconds for MPLS restorations and several seconds for optical WSON restorations.

Resource Utilization Liu et al. [510] proposed a method to improve resource utilization and to reduce transmission latencies through the processes of virtualization and service abstraction. A centralized SDN control implements the service abstraction layer (to enable SDN orchestrations) in order to integrate the network topology management (across both IP and WDM), and the spectrum resource allocation in a single control platform. The SDN orchestrator also achieves dynamic and simultaneous connection establishment across both IP and OTN layers reducing the transmission latencies. The control plane design is split between local (child) and root (parent) controllers. The local controller realizes the label switched paths on the optical nodes while the root controller realizes the forwarding rules for realizing the IP layer. Experimental evaluation of average transfer time measurements showed IP layer latencies on the order of several milliseconds, and several hundreds of milliseconds for the OTN latencies, validating the feasibility of control plane unification for IP over optical transport networks.

Virtual Optical Networks (VONs) Vilalta et al. [511] presented controller orchestration to integrate multiple transport network technologies, such as IP and GMPLS. The proposed architectural framework devises VONs to enable the virtualization of the physical resources within each domain. VONs are managed by lower level physical controllers (PCs), which are hierarchically managed by an SDN network orchestrator (NO). Network Virtualization Controllers (NVC) are introduced (on top of the NO) to abstract the virtualized multilayers across multiple domains. End-to-end provisioning of VONs is facilitated through hierarchical control interaction over three levels, the customer controller, the NO&NVCs, and the PCs. An experimental evaluation demonstrated average VON provisioning delays on the order of several seconds (5 s and 10 s), validating the flexibility of dynamic VON deployments over the optical transport networks. Longer provisioning delays may impact the network application requirements, such as failure recovery processes, congestion control, and traffic engineering. General pitfalls of such hierarchical structures are increased control plane complexity, risk of controller failures, and maintenance of reliable communication links between control plane entities.

2.7.2 Multidomain Orchestration

Large scale network deployments typically involve multiple domains, which have often heterogeneous layer technologies. Achieve high utilization of the networking resources while provisioning end-to-end network paths and services across multiple domains and their respective layers and respective technologies is highly challenging [519–521]. Multidomain SDN orchestration studies have sought to exploit the unified SDN control plane to aid the resource-efficient provisioning across the multiple domains.

2.7.2.1 General Multidomain Networks

Optical Multitechnologies Across Multiple Domains Optical nodes are becoming increasingly reconfigurable (e.g., through variable BVTs and OFDM transceivers, see Section 2.3), adding flexibility to the switching elements. When a single end-to-end service establishment is considered, it is more likely that a service is supported by different optical technologies that operate across multiple domains. Yoshida et al. [498] have demonstrated SDN based orchestration with emphasis on the physical interconnects between multiple domains and multiple technology specific controllers so as to realize end-to-end services. OpenFlow capabilities have been extended for fixed-length variable capacity optical packet switching [522]. That is, when an optical switch matches the label on an incoming optical packet, if a rule exists in the switch (flow entry in the table) for a specific label, a defined action is performed on the optical packet by the switch. Otherwise, the optical packet is dropped and the controller is notified. Interconnects between optical packet switching networks and elastic optical networks are enabled through a novel OPS-EON interface card. The OPS-EON interface is designed as an extension to a reconfigurable, programmable and flexi-grid EON supporting the OpenFlow protocol. The testbed implementation of OPS-EON interface cards demonstrated the orchestration of multiple domain controllers and the reconfigurability of FL-VC OPS across multidomain, multilayer, multitechnology scenarios.

Hierarchical Multidomain Control Jing et al. [512] have also examined the integration of multiple optical transport technologies from to multiple vendors across multiple domains, focusing on the control mechanisms across multiple domains. Jing et al. proposed hierarchical SDN orchestration with parent and domain controllers.

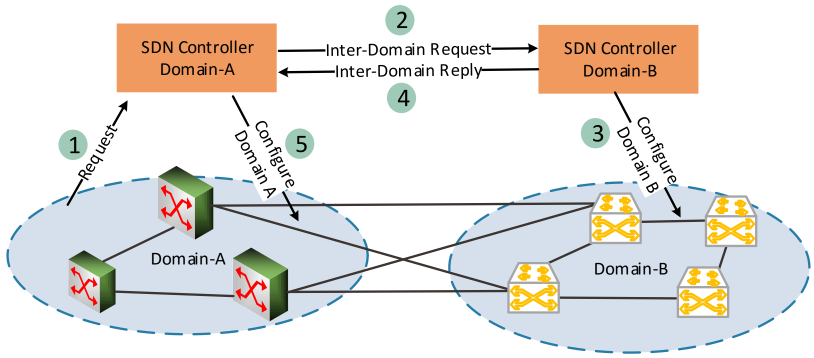


Figure 2.21: Inter-domain lightpath provisioning mechanism.

Domain controllers abstract the physical layer by virtualizing the network resources. A Parent Controller (PC) encompasses a Connection Controller (CC) and a Routing Controller (RC) to process the abstracted virtual network. When a new connection setup request is received by the PC, the RC (within the PC) evaluates the end-to-end routing mechanisms and forwards the information to the CC. The CC breaks the end-to-end routing information into shorter link segments belonging to a domain. Segmented routes are then sent to the respective domain controllers for link provisioning over the physical infrastructures. The proposed mechanism was experimentally verified on a testbed built with the commercial OTN equipment.

Inter-Domain Protocol Zhu et al. [513] followed a different approach for the SDN multidomain control mechanisms by considering the flat arrangement of controllers as shown in Fig. 2.21. Each domain is autonomously managed by an SDN controller specific to the domain. An Inter-Domain Protocol (IDP) was devised to establish the communication between domain specific controllers to coordinate the lightpath setup across multiple domains. Zhu et al. also proposed a Routing and Spectrum Allocation (RSA) algorithm for the end-to-end provisioning of services in the SD-EONs. The distributed RSA algorithm operates on the domain specific controllers using the IDP protocol. The RSA considers both transparent lightpath connections, i.e., all-optical

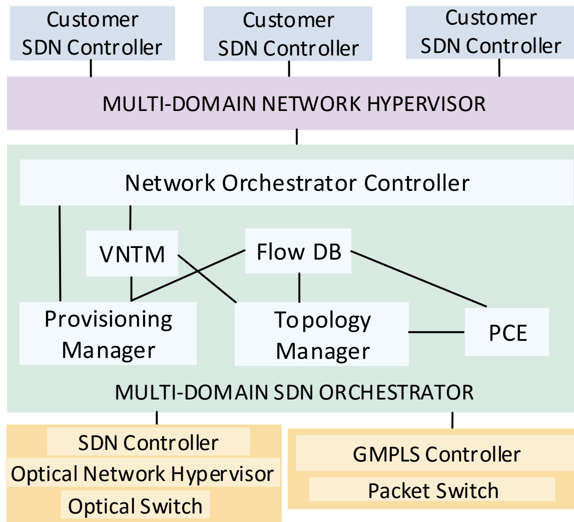


Figure 2.22: Illustration of multilevel virtualization.

lightpath, and translucent lightpath connections, i.e., optical-electrical-optical connections. The benefit of such techniques is privacy, since the domain specific policies and topology information are not shared among other network entities. Neighbor discovery is independently conducted by the domain specific controller or can initially be configured. A domain appears as an abstracted virtual node to all other domain specific controllers. Each controller then assigns the shortest path routing within a domain between its border nodes. An experimental setup validating the proposed mechanism was demonstrated across geographically-distributed domains in the USA and China.

Multidomain Network Hypervisors Vilalta et al. [514] presented a mechanism for virtualizing multitechnology optical, multitenant networks. The Multidomain Network Hypervisor (MNH) creates customer specific virtual network slices managed by the customer specific SDN controllers (residing at the customers' locations) as illustrated in Fig. 2.22. Physical resources are managed by their domain specific physical SDN controllers. The MNH operates over the network orchestrator and physical SDN

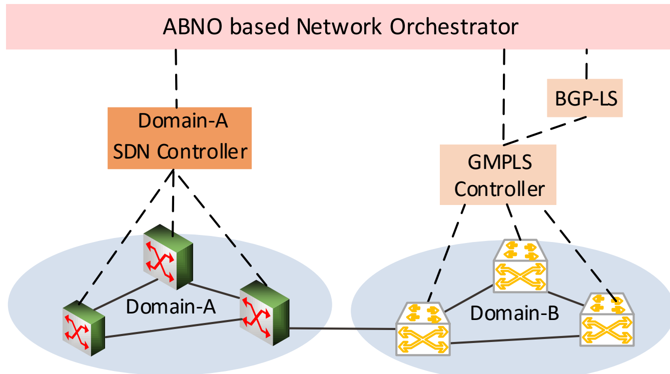


Figure 2.23: The application-based network operations (ABNO) [18]

controllers for provisioning VONs on the physical infrastructures. The MNHs abstracts both (*i*) multiple optical transport technologies, such as optical packet switching and Elastic Optical Networks (EONs), and (*ii*) multiple control domains, such as GMPLS and OpenFlow. Experimental assessments on a testbed achieved VON provisioning within a few seconds (5 s), and control overhead delay on the order of several tens of milliseconds. Related virtualization mechanisms for multidomain optical SDN networks with end-to-end provisioning have been investigated in [523, 524].

Application-Based Network Operations Muñoz et al. [18], have presented an SDN orchestration mechanism based on the application-based network operations (ABNO) framework, which is being defined by the IETF [525]. The ABNO based SDN orchestrator integrates OpenFlow and GMPLS in transport networks. Two SDN orchestration designs have been presented: (*i*) with centralized physical network topology aware path computation (illustrated in Fig. 2.23), and (*ii*) with topology abstraction and distributed path computation. In the centralized design, OpenFlow and GMPLS controllers (lower level control) expose the physical topology information to the ABNO-orchestrator (higher level control). The PCE in the ABNO-orchestrator has the global view of the network and can compute end-to-end paths with complete knowledge of the network. Computed paths are then provisioned through the lower level controllers. The pitfalls of such centralized designs are (*i*) computationally intensive path computations, (*ii*) continuous updates of topology and traffic information, and (*iii*) sharing of confidential network information and policies with other network elements. To reduce the computational load at the orchestrator, the second design implements distributed path computation at the lower level controllers (instead of path computation at the centralized orchestrator). However, such distributed mechanisms may lead to suboptimal solutions due to the limited network knowledge.

2.7.2.2 Multidomain Data Center Orchestration

Control Architectures Geographically distributed DCs are typically interconnected by links traversing multiple domains. The traversed domains may be homogeneous i.e., have the same type of network technology, e.g., OpenFlow based ROADMs, or may be heterogeneous, i.e., have different types of network technologies, e.g., OpenFlow based ROADMs and GMPLS based WSON. The SDN control structures for a multidomain network can be broadly classified into the categories of (*i*) single SDN orchestrator/controller, (*ii*) multiple mesh SDN controllers, and (*iii*) multiple hierarchical SDN controllers [515, 516]. The single SDN orchestrator/controller has to support heterogeneous SBIs in order to operate with multiple heterogeneous domains, e.g., the Path Computation Element Protocol (PCEP) for GMPLS network domains and the OpenFlow protocol for OpenFlow supported ROADMs. Also, domain specific details, such as topology, as well as network statistics and configurations, have to be exposed to an external entity, namely the single SDN orchestrator/controller, raising privacy concerns. Furthermore, a single controller may result in scalability issues. Mesh SDN control connects the domain-specific controllers side-by-side by extending the east/west bound interfaces. Although mesh SDN control addresses the scalability and privacy issues, the distributed nature of the control mechanisms may lead to sub-

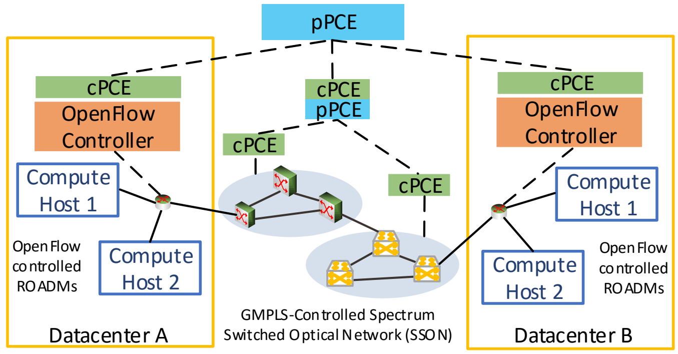


Figure 2.24: Illustration of SDN orchestration based on Hierarchical Path Computation Element (H-PCE) [19].

optimal solutions. With hierarchical SDN control, a logically centralized controller (parent SDN controller) is placed above the domain-specific controllers (child SDN controllers), extending the north/south bound interfaces. Domain-specific controllers virtualize the underlying networks inside their domains, exposing only the abstracted view of the domains to the parent controller, which addresses the privacy concerns. Centralized path computation at the parent controller can achieve optimal solutions. Multiple hierarchical levels can address the scalability issues. These advantages of hierarchal SDN control are achieved at the expense of an increased number of network entities, resulting in the operational complexities.

Hierarchical PCE Casellas et al. [19] considered DC connectivities involving both intra-DC and inter-DC communications. Intra-DC communications enabled through OpenFlow networks are supported by an OpenFlow controller. The inter-DC communications are enabled by optical transport networks involving more complex control, such as GMPLS, as illustrated in Fig. 2.24. To achieve the desired SDN benefits of flexibility and scalability, a common centralized control platform spanning across heterogeneous control domains is proposed. More specifically, an Hierarchical PCE (H-PCE) aggregates PCE states from multiple domains. The end-to-end path setup between DCs is orchestrated by a parent-PCE (pPCE) element, while the paths are provisioned by the child-PCEs (cPCEs) on the physical resources, i.e., the OpenFlow and GMPLS domains. The proposed mechanism utilizes existing protocol interfaces, such as BGP-LS and PCEP, which are extended with OpenFlow to support the H-PCE.

Virtual-SDN Control Muñoz et al. [517, 518] proposed a mechanism to virtualize the SDN control functions in a DC/cloud by integrating SDN with Network Function Virtualization (NFV). In the considered context, NFV refers to realizing network functions by software modules running on generic computing hardware inside a DC; these network functions were conventionally implemented on specialized hardware modules. The orchestration of Virtual Network Functions (VNFs) is enabled by an integrated SDN and NFV management which dynamically instantiates virtual SDN controllers. The virtual SDN controllers control the Virtual Tenant Networks (VTNs), i.e., virtual multidomain and multitechnology networks. Multiple VNFs running on a Virtual Machine (VM) in a DC are managed by a VNF manger. A virtual SDN controller is responsible for creating, managing, and tearing down the VNF achieving the flexibility in the control plane management of the multilayer and the multidomain networks. Additionally, as an extension to the proposed mechanism, the virtualization of the control functions of the LTE Evolved Packet Core (EPC) has been discussed in [526].

2.7.3 Orchestration: Summary and Discussion

Relatively few SDN orchestration studies to date have focused on vertical multilayer networking within a given domain. The few studies have developed two general orchestration frameworks and have examined a few orchestration strategies for some specific applications. More specifically, one orchestration framework has focused on optimal bandwidth allocation based mainly on congestion [503], while the other framework has focused on exploiting application traffic tolerances for delays for efficiently routing traffic [508]. SDN orchestration of vertical multilayer optical networking is thus still a relatively little explored area. Future research can develop orchestration frameworks that accommodate the specific optical communication technologies in the various layers and rigorously examine their performance-complexity tradeoffs. Similarly, relatively few applications have been examined to date in the application-specific orchestration studies for vertical multilayer networking [509–511]. The examination of the wide range of existing applications and any newly emerging network application in the context of SDN orchestrated vertical multilayer networking presents rich research opportunities. The cross-layer perspective of the SDN orchestrator over a given domain could, for instance, be exploited for strengthening security and privacy mechanisms or for accommodating demanding real-time multimedia.

Relatively more SDN orchestration studies to date have examined multidomain networking than multilayer networking (within a single domain). As the completed multidomain orchestration studies have demonstrated, the SDN orchestration can help greatly in coordinating complex network management decisions across multiple distributed routing domains. The completed studies have illustrated the fundamental tradeoff between centralized decision making in a hierarchical orchestration structure and distributed decision making in a flat orchestration structure. In particular, most studies have focused on hierarchical structures [19, 512, 517], while only one study has mainly focused on a flat orchestration structure [513]. In the context of DC internetworking, the studies [515, 516] have sought to bring out the tradeoffs between these two structures by examining a range of structures from centralized to distributed. While centralized orchestration can make decisions with a wide knowledge horizon across the states in multiple domains, distributed decision making preserves the privacy of network status information, reduces control traffic, and can make fast localized decisions. Future research needs to shed further light on these complex tradeoffs for a wide range of combinations of optical technologies employed in the various domains. Throughout, it will be critical to abstract and convey the key characteristics of optical physical layer components and switching nodes to the overall orchestration protocols. Optimizing each abstraction step as well as the overall orchestration and examining the various performance tradeoffs are important future research directions.

2.8 OPEN CHALLENGES AND FUTURE SDON RESEARCH DIRECTIONS

We have outlined open challenges and future Software Defined Optical Network (SDON) research directions for each sub-category of surveyed SDON studies in the Summary and Discussion subsections in the preceding survey sections. In this section, we focus on the overall cross-cutting open challenges that span across the preceding considered categories of SDON studies. That is, we focus on open challenges and research directions that span the vertical (inter-layer) and horizontal (inter-domain) SDON aspects. The vertical SDON aspects encompass the seamless integration of the various (vertical) layers of the SDON architecture; especially the optical layer, which is not considered in general SDN technology. The horizontal SDON aspects include the integration of SDONs with existing non-SDN optical networking elements, and the internetworking with other domains, which may have similar or different SDN architectures. A key challenge for SDON research is to enable the use of SDON concepts in operational real-time network infrastructures. Importantly, the SDON concepts need to demonstrate performance gains and cost reductions to be considered by network and service providers. Therefore, we cater some of the open challenges and future directions towards enabling and demonstrating the successful use of SDON in operational networks.

The SDON research and development effort to date have resulted in insights for making the use of SDN in optical transport networks feasible and have demonstrated advantages of SDN based optical network management. However, most network and service providers depend on optical transport to integrate with multiple industries to complete the network infrastructure. Often, network and service providers struggle to integrate hardware components and to provide accessible software management to customers. For example, companies that develop hardware optical components do not always have a complete associated software stack for the hardware components. Thus, network and service providers using the hardware optical components often have to maintain a software development team to integrate the various hardware components through software based management into their network, which is often a costly endeavor. Thus, improving SDN technology so that it seamlessly integrates with components of various industries and helps the integration of components from various industries is an essential underlying theme for future SDON research.

2.8.1 Simplicity and Efficiency

Optical network structures typically span heterogeneous devices ranging from the end user nodes and local area networks via ONUs and OLTs in the access networks to edge routers and metro network nodes and on to backbone (core) network infrastructures. These different devices often come from different vendors. The heterogeneity of devices and their vendors often requires manual configuration and maintenance of optical networks. Moreover, different communication technologies typically require the implementation of native functions that are specific to the communication technology characteristics, e.g., the transmission and propagation properties. By centralizing the optical network control in an SDN controller, the SDN networking paradigm creates a unified view of the entire optical network. The specific native functions for specific communication devices can be migrated to the software layer and be implemented by a central node, rather than through manual node-by-node configurations. The central node would typically be readily accessible and could reduce the required physical accesses to distributed devices at their on-site locations. This centralization can simplify the network management and reduce operational expenditures. An important challenge in this central management is the efficient SDN control of components from multiple vendors. Detailed vendor contract specifications of open-source middleware may be needed to efficiently control components from different vendors.

The heterogeneity of devices may reduce the efficiency of network infrastructures due to the required multiple software and hardware modules for a complete networking solution. Future research should investigate efficient mechanisms for making complete networking solutions available for specific use cases. For example, the use of SDON for an access network provider may require multiple SDN controllers co-located within the OLT to enable the control of the access network infrastructure from one central location. While the SDON studies reviewed in this survey have led initial investigations of simple and dynamic network management, future research needs to refine these management strategies and optimize their operation across combinations of network architecture structures and across various network protocol layers. Simplicity is an essential part of this challenge, since overly complicated solutions are generally not deployed due to the risk of high expenditures.

2.8.2 North Bound Interface

The NorthBound Interface (NBI) comprises the communication from the controller to the applications. This is an important area of future research as applications and their needs are generally the driving force for deploying SDON infrastructures. Any application, such as video on demand, VoIP, file transfer, or peer-to-peer networking, is applied from the NBI to the SDN controller which consequently conducts the necessary actions to implement the service behaviors on the physical network infrastructure. Applications often require specific service behaviors that need to be implemented on the overall network infrastructure. For example, applications requiring high data rates and reliability, such as Netflix, depend on data centers and the availability of data from servers with highly resilient failure protection mechanisms. The associated management network needs to stack redundant devices as to safeguard against outages. Services are provided as policies through the NBI to the SDN controller, which in turn generates flow rules for the switching devices. These flow rules can be prioritized based on the customer use cases. An important challenge for future NBI research is to provide a simple interface for a wide variety of service deployments without vendor lock-in, as vendor lock-in generally drives costs up. Also, new forms of communication to the controller, in addition to current techniques, such as REpresentational State Transfer (REST) [157] and HTTP, should be researched. Moreover, future research should develop an NBI framework that spans horizontally across multiple controllers, so that service customers are not restricted to using only a single controller.

Future research should examine control mechanisms that optimally exploit the central SDN control to provide simple and efficient mechanisms for automatic network management and dynamic service deployment [527]. The NBI of SDONs is a challenging facet of research and development because of the multitude of interfaces that need to be managed on the physical layer and transport layer. Optical physical layer components and infrastructures require high capital and operational expenditures and their management is generally not associated with network or service providers but rather with optical component/infrastructure vendors. Future research should develop novel Application Program Interfaces (APIs) for optical layer components and infrastructures that facilitate SDN control and are amenable to efficient NBI communication. Essentially, the challenge of efficient NBI communication with the SDN controller should be considered when designing the APIs that interface with the physical optical layer components and infrastructures.

One specific strategy for simplifying network management and operation could be to explore the grouping of control policies of similar service applications, e.g., applications with similar QoS requirements. The grouping can reduce the number of control policies at the expense of slightly coarser granularity of the service offerings. The emerging Intent-Based Networking (IBN) paradigm, which drafts intents for services and policies, can provide a specific avenue for simplifying dynamic automatic configuration and virtualization [528, 529]. Currently network applications are deployed based on how the network should behave for a specific action. For example, for inter domain routing, the Border Gateway Protocol (BGP) is used, and the network gateways are configured to communicate with the BGP protocol. This complicates the provisioning of services that typically require multiple protocols and limits the flexibility of service provisioning. With IBN, the application gives an intent, for example, transferring video across multiple domains. This intent is then associated with automated dynamic configurations of the network elements to communicate data over the domains using appropriate protocols. The grouping of service policies, such as intents, can facilitate easy and dynamic service provisioning. Intent groups can be described in a graph to simplify the compilation of service policies and to resolve conflicts [530].

2.8.3 Reliability, Security, and Privacy

The SDN paradigm is based on a centrally managed network. Faulty behaviors, security infringements, or failures of the control would likely result in extensive disruptions and performance losses that are exacerbated by the centralized nature of the SDN control. Instances of extensive disruptions and losses due to SDN control failures or infringements would likely reduce the trust in SDN deployments. Therefore, it is very important to ensure reliable network operation [531] and to provision for security and privacy of the communication. Hence, reliability, security, and privacy are prominent SDON research challenges. Security in SDON techniques is a fairly open research area, with only few published findings. As a few reviewed studies (see Section 2.6.4) have explored, the central SDN control can facilitate reliable network service through speeding up failure recovery. The central SDN control can continuously scan the network and the status messages from the network devices. Or, the SDN control can redirect the status messages to a monitoring service that analyzes the data network. Security breaches can be controlled by broadcasting messages from the controller to all affected devices to block traffic in a specific direction. Future research should refine these reliability functions to optimize automated fault and performance diagnostics and reconfigurations for quick failure recovery.

Network failures can either occur within the physical layer infrastructure, or as errors within the higher protocol layers, e.g., in the classical data link (L2), network (L3), of transport (L4) layers. In the context of SDONs, physical layer failures present important future research opportunities. Physical layer devices need to be carefully monitored by sending feedback from the devices to the controller. The research and development on communication between the SDN controller and the network devices has mainly focused on sending flow rules to the network devices while feedback communicated from the devices to the controller has received relatively little attention. For example, there are three types of OpenFlow messages, namely Packet-In, Packet-Out, and Flow-Mod. The Packet-In messages are sent from the OpenFlow switches to the controller, the Packet-Out message is sent from the controller to the device, and the Flow-Mod message is used to modify and monitor the flow rules in the flow table.

Future research should examine extensions of the Packet-In message to send specific status updates in support of network and device failure monitoring to the controller. These status messages could be monitored by a dedicated failure monitoring service. The status update messages could be broadly defined to cover a wide range of network management aspects, including system health monitoring and network failure protection.

A related future research direction is to secure configuration and operation of SDONs through trusted encryption and key management systems [119]. Moreover, mechanisms to ensure the privacy of the communication should be explored. The security and privacy mechanisms should strive to exploit the natural immunity of optical transmission segments to electro-magnetic interferences.

In summary, security and privacy of SDON communication are largely open research areas. The optical physical layer infrastructure has traditionally not been controlled remotely, which in general reduces the occurrences of security breaches. However, centralized SDN management and control increase the risk of security breaches, requiring extensive research on SDON security, so as to reap the benefits of centralized SDN management and control in a secure manner.

2.8.4 Scalability

Optical networks are expensive and used for high-bandwidth services, such as long-distance network access and data center interconnections. Optical network infrastructures either span long distances between multiple geographically distributed locations, or could be short-distance incremental additions (interconnects) of computing devices. Scalability in multiple dimensions is therefore an important aspect for future SDON research. For example, a myriad of tiny end devices need to be provided with network access in the emerging Internet of Things (IoT) paradigm [355]. The IoT requires access network architectures and protocols to scale vertically (across protocol layers and technologies) and horizontally (across network domains). At the same time, the ongoing growth of multimedia services requires data centers to scale up optical network bandwidths to maintain the quality of experience of the multimedia services. Broadly speaking, scalability includes in the vertical dimension the support for multiple network devices and technologies. Scalability in the horizontal direction includes the communication between a large number of different domains as well as support for existing non-SDON infrastructures.

A specific scalability challenge arising with SDN infrastructure is that the scalability of the control plane (OpenFlow protocol signalling) communication and the scalability of the data plane communication which transports the data plane flows need to be jointly considered. For example, the Openflow protocol 1.4 currently supports 34 Flow-Mod messages [532], which can communicate between the network devices and the controller. This number limits the functionality of the SBI communication. Recent studies have explored a protocol-agnostic approach [151, 533], which is a data plane protocol that extends the use of multiple protocols for communication between the control plane and data plane. The protocol-agnostic approach resolves the challenges faced by OpenFlow and, in general, any particular protocol. Exploring this novel protocol-agnostic approach presents many new SDON research directions.

Scalability would also require SDN technology to overlay and scale over existing non-SDN infrastructures. Vendors provide support for known non-SDN devices, but this area is still a challenge. There are no known protocols that could modify the flow tables of existing popularly described "non-OpenFlow" switches. In the case of optical networks, as SDN is still being incrementally deployed, the overlaying with non-SDN infrastructure still requires significant attention. Ideally, the overlay mechanisms should ensure seamless integration and should scale with the growing deployment of SDN technologies while incurring only low costs. Overall, scalability poses highly important future SDON research directions that require economical solutions.

2.8.5 Standardization

Networking protocols have traditionally followed a uniform standard system for all the communication across multiple domains. Standardization has helped vendors to provide products that work in and across different network infrastructures. In order to ensure the compatible inter-operation of SDON components (both hardware and software) from a various vendors, key aspects of the inter-operation protocols need to be standardized. Towards the standardization goal, communities, such as Open Networking Foundation (ONF), have created boards and committees to standardize protocols, such as OpenFlow. Standardization should ensure that SDON infrastructures can be flexibly configured and operated with components from various vendors. The use of open-source software can further facilitate the inter-operation. Proprietary hardware and software components generally create vendor lock-in, which restricts the flexibility of network operation and reduces the innovation of network and service providers.

As groundwork for standardization, it may be necessary to develop and optimize a common (or a small set) of SDON architectures and network protocol configurations that can serve as a basis for standardization efforts. The standardization process may involve a common platform that is built thorough the cooperation of multiple manufacturers. Another thrust of standardization groundwork could be the development of open-source software that supports SDON architectures. For example, Openstack is a cloud based management framework that has been adopted and supported by multiple networking vendors. Such efforts should be extended to SDONs in future work.

2.8.6 Multilayer Networking

As discussed in Section 2.7, multilayer networking involves vertical multilayer networking across the vertical layers as well as horizontal multilayer (multidomain) networking across multiple domains. We proceed to outline open challenges and future research directions for vertical multilayer networking in the context of SDON, which includes an optical physical layer, in this subsection. Horizontal multilayer (multidomain) networking is considered in Section 2.8.7.

For the vertical multilayer networking in a single domain, the optical physical layer is the key distinguishing feature of SDONs compared to conventional SDN architectures for general IP networks. Most of the higher layers in SDONs have similar multilayer networking challenges as general IP networks. However, the optical physical layer requires the provisioning of specific optical transmission parameters, such as wavelengths and signal strengths. These parameters are managed by optical devices, such as the OLT in PON networks. For SDON networks, so-called *optical orchestrators*, which are commercially available, e.g., from ADVA Optical Networking, provide a single interface to provision the optical layer parameters. We illustrate this optical orchestrator layer in the context of an SDON multilayer network in the rightmost branch of Fig. 2.2. The optical orchestrator resides above the optical devices and below the SDN controller. The optical orchestrator uses common SDN SBI interface protocols, such as OpenFlow, to communicate with the optical devices in the south-bound direction and with the controller in the north-bound direction.

The SDN controller in the control plane is responsible for the management of the SDN-enabled switches, potentially via an optical orchestrator. Communicating over the SBI using different protocols can be challenging for the controller. This challenge can be addressed by using south-bound renderers. South-bound renderers are APIs that reside within the controller and provide a communication channel to any desired SBI protocol. Most SDN controllers currently have an OpenFlow renderer to be able to communicate to Openflow network switches. But there are also SNMP and NETCONF-based renderers, which communicate with traditional non-OpenFlow switches. This enables the existence of hybrid networks with already existing switches. The effective support of such hybrid networks, in conjunction with appropriate south-bound renderers and optical orchestrators, is an important direction for future research.

2.8.7 Multidomain Networks

A network domain usually belongs to a single organization that owns (i.e., financially supports and uses) the network domain. The management of multidomain networking involves the important aspects of configuring the access control as well as the authentication, authorization, and accounting. Efficient SDN control mechanisms for configuring these multidomain networking aspects is an important direction for future research and development.

Multidomain SDONs may also need novel routing algorithm that enhance the capabilities of the currently used BGP protocol. Multidomain research [534] has now taken interest in the Intent-Based Networking (NBI) paradigm for SDN control, where Intent-APIs can solve the problems of spanning across multiple domains. For instance, the intent of an application to transfer information across multiple domains is translated into service instances that access configurations between domains that have been pre-configured based on contracts. Currently, costly manual configurations between domains are required for such applications. Future research needs to develop concrete models for NBI based multidomain networking in SDONs.

2.8.8 Fiber-Wireless (FiWi) Networking

The optical (fiber) and wireless network domains have many differences. At the physical layer, wireless networks are characterized by varying channel qualities, potentially high losses, and generally lower transmission bit rates than optical fiber. Wireless end nodes are typically mobile and may connect dynamically to wireless network domains. The mobile wireless nodes are generally the end-nodes in a FiWi network and connect via intermediate optical nodes to the Internet. Due to these different characteristics, the management of wireless networks with mobile end nodes is very different from the management of optical network nodes. For example, wireless access points should maintain their own routing table to accommodate access to dynamically connected mobile devices. Combining the control of both wireless and optical networks in a single SDN controller requires concrete APIs that handle the respective control functions of wireless and optical networks. Currently, service providers maintain separate physical management services without a unified logical control and management plane for FiWi networks. Developing integrated controls for FiWi networks can be viewed as a special case of multilayer networking and integration.

Developing specialized multilayer networking strategies for FiWi networks is an important future research directions as many aspects of wireless networks have dramatically advanced in recent years. For instance, the cell structure of wireless cellular networks [535] has advanced to femtocell networks [536] as well as heterogeneous and multitier cellular structures [537, 538]. At the same time, machine-to-machine communication [539, 540] and energy savings [541, 542] have drawn research attention.

2.8.9 QoS and Energy Efficiency

Different types of applications have vastly different traffic bit rate characteristics and QoS requirements. For instance, streaming high-definition video requires high bit rates, but can tolerate some delays with appropriate playout buffering. On the other hand, VoIP (packet voice) or video conference applications have typically low to moderate bit rates, but require low latencies. Achieving these application-dependent QoS levels in an energy-efficient manner [542–544] is an important future research direction. A related future research direction is to exploit SDN control for QoS adaptations of real-time media and broadcasting services. Broadcasting services involve typically data rates ranging from 3–48 Gb/s to deliver video at various resolutions to the users within a reasonable time limit. In addition to managing the QoS, the network has to manage the multicast groups for efficient routing of traffic to the users. Recent studies [545, 546] discuss the potential of SDN, NFV, and optical technologies to achieve the growing demands of broadcasters and media. Moreover, automated provisioning strategies of QoS and the incorporation of quality of protection and security with traditional QoS are important direction for future QoS research in SDONs.

2.8.10 Performance Evaluation

Comprehensive performance evaluation methodologies and metrics need to be developed to assess the SDON designs addressing the preceding future research directions ranging from simplicity and efficiency (Section 2.8.1) to optical-wireless networks (Section 2.8.8). The performance evaluations need to encompass the data plane, the control plane, as well as the overall data and control plane interactions with the SDN interfaces and need to take virtualization and orchestration mechanisms into consideration. In the case of the SDON infrastructure, the performance evaluations will need include the optical physical layer [547]. While there have been some efforts to develop evaluation frameworks for general SDN switches [548, 549], such evaluation frameworks need to be adapted to the specific characteristics of SDON architectures. Similarly, some evaluation frameworks for general SDN controllers have been explored [550, 551]; these need to be extended to the specific SDON control mechanisms.

Generally, performance metrics obtained with SDN and virtualization mechanisms should be benchmarked against the corresponding conventional network without any SDN or virtualization components. Thus, the performance tradeoffs and costs of the flexibility gained through SDN and virtualization mechanism can be quantified. This quantified data would then need to be assessed and compared in the context of business needs. To identify some of the important aspects of performance we analyze the sample architecture in Fig. 2.14. The SDN controller in the SDON architecture in Fig. 2.14 spans across multiple elements, such as ONUs, OLTs, routers/switches in the metro-section, as well as PCEs in the core section. A meaningful performance evaluation of such a network requires comprehensive analysis of data plane performance aspects and related metrics, including noise spectral analysis, bandwidth and link rate monitoring, as well as evaluation of failure resilience. Performance evaluation mechanisms need to be developed to enable the SDON controller to obtain and analyze these performance data. In addition, mechanisms for control layer performance analysis are needed. The control plane performance evaluation should, for instance assess the controller efficiency and performance characteristics, such as the OpenFlow message rates and the rates and delays of flow table management actions.

2.9 CONCLUSION

We have presented a comprehensive survey of software defined optical networking (SDON) studies to date. We have mainly organized our survey according to the

SDN infrastructure, control, and application layer structure. In addition, we have dedicated sections to SDON virtualization and orchestration studies. Our survey has found that SDON infrastructure studies have examined optical (photonic) transmission and switching components that are suitable for flexible SDN controlled operation. Moreover, flexible SDN controlled switching paradigms and optical performance monitoring frameworks have been investigated.

SDON control studies have developed and evaluated SDN control frameworks for the wide range of optical network transmission approaches and network structures. Virtualization allows for flexible operation of multiple Virtual Optical Networks (VONs) over a given installed physical optical network infrastructure. The surveyed SDON virtualization studies have examined the provisioning of VONs for access networks, exploiting the specific physical and Medium Access Control (MAC) layer characteristics of access networks. The virtualization studies have also examined the provisioning of VONs in metro and backbone networks, examining algorithms for embedding the VON topologies on the physical network topology under consideration of the optical transmission characteristics.

SDON application layer studies have developed mechanisms for achieving Quality of Service (QoS), access control and security, as well as energy efficiency and failure recovery. SDON orchestration studies have examined coordination mechanisms across multiple layers (in the vertical dimension of the network protocol layer stack) as well as across multiple network domains (that may belong to different organizations).

While the SDON studies to date have established basic principles for incorporating and exploiting SDN control in optical networks, there remain many open research challenges. We have outlined open research challenges for each individual category of studies as well as cross-cutting research challenges.

CHAPTER 3

R-FFT: FUNCTIONAL SPLIT AT IFFT/FFT IN UNIFIED LTE AND CABLE ACCESS NETWORK

3.1 INTRODUCTION

3.1.1 Motivation

Today the user Internet connectivity has been dominated by the cellular wireless and cable/DSL access network technologies For a long time, wireless technologies, such as LTE have enjoyed large growth opportunities due to the proliferation of wireless smart phones and hand-held devices in contrast to the cable technologies [552]. With the recent development of DOCSIS 3.1 specifications for cable technologies, Multi-System Operators (MSOs) are able to offer the services which are equivalent to the advance wireless technologies supporting gigabit connectivity to the users in both upstream and downstream [553]. The next generation 5G technology [554] focuses on the unification of heterogeneous platforms at the access, backhaul and core networks especially through the softwarization and virtualization of the network infrastructures. Towards this end, integration of cable and wireless technologies could be the first step in the process of unifying the heterogeneous access platform. 5G is also envisioned to support a wide range of applications ranging from lower data rate Internet of Things (IoT) to ultra-reliable health monitoring, and larger data rates for 4K HD video streaming [28]. Challenges in the 5G technologies [555] include backhaul complexity resulting from densification of radio nodes, interference with the neighboring cells and network deployment costs [556]. Promising technologies, such as Software Defined Optical Networking (SDN) [557] and Network Function Virtualization (NFV) [558] are not only addressing the challenges posed by 5G but also facilitating the faster integration of heterogeneous-access networks while supporting the larger date rate, lower latencies and high reliability. Moreover, current network infrastructures for both wireless and cable technologies can rely on common optical fiber technologies, such as optical digital Ethernet [559]. Therefore, MSOs are showing large interests in converging to a common access platform through generic protocols and standardization, such as CPRI [560] for integration of heterogeneous infrastructures.

3.1.2 Overview of Softwarization

3.1.2.1 Cloud-Radio Access Networks (CRAN)

Softwarization of network functions can fundamentally reduce implementation complexity while increasing the flexibility [561]. Software implementation of the RAN functions in a cloud environment is referred to as Cloud-RAN or CRAN [562]. In the CRAN, the functional implementation of the Radio Access Network (RAN) is split between Remote Radio Units (RRUs) which corresponds to antenna units with RF passband processing capabilities for the physical transmission of the signal, and Base Band Units (BBUs) which implements the complementary baseband signal processing. Communication between CRAN and RRU is typically enabled by optical technologies, such as Passive Optical Networks (PON) and Optical Wavelength Division Multiplexing. Traditionally, the connection between RRU and BBU is established by a cable RF link. Cable RF contributes towards considerable signal degrade for the larger distances between RRU and BBU. In contrast to downlink signals, signal degrade in the uplink direction has more negative consequences due to the lower signal levels. The signal degrade between BBU and RRU can be avoided by digitizing the RF signal and transmitting the digitized symbols over an optical fiber.

As noted earlier, important aspect of the RRUs in the context of CRAN is the reduced complexity in radio equipment hardware which results in lower CAPEX/OPEX for the large scale deployment of small cells. RRUs in a building environment are also referred to as Distributed Antenna Systems (DAS) [563]. DAS play an important role in realizing the large number of small cell deployments in meeting the coverage and capacity demands for indoor applications. Centralization of BBU can support multiple RRUs which can provide a common platform for the centralized management of resources. BBUs are typically implemented on a generic computing hardware, where by a specific virtual machine (VM) implements the base band processing operations on a virtualized hardware [564].

3.1.2.2 Distributed Converged Cable Access Platform (DCCAP) Architectures

Connectivity to the Cable Modems (CM) in the Hybrid Fiber Coax (HFC) network is delivered in part by optical and in part by cable segment. The Cable Modem Termination System (CMTS) connects the CMs to Central Office (CO)/headend through the protocol defined by Data Over Cable Service Interface Specifications (DOCSIS). In the traditional HFC network deployments, analog signals from the CMTS are carried over an optical link to a remote analog fiber node where the signal is converted to analog RF signal which can be transmitted over the cable link. But, an analog signal over an optical fiber gradually degrades as the optical propagation distance is increased limiting the effective HFC operational distance (i.e., from the headend to CM). Modular Headend Architecture version 2 (MHAv2) allows CMTS functions to be implemented in a modular fashion allowing some of the modular entities to be implemented at the newly designed digital remote nodes. In order to improve the signal quality over the cable segment, the remote nodes are connected to headend through the digital optical link where the remote node can be deployed in close proximity to the users reducing the effective cable length. Distributed Converged Cable Access Platform (DCCAP) architecture implements the modular CMTS functions at the remote nodes. Remote node is similar to a RRU in the CRAN whereby the RAN implementation at the cloud is similar to CMTS implementation at the headend. The Remote-PHY (R-PHY) and Remote-MACPHY (R-MACPHY) technology of the DCCAP extends the modular

CMTS and modular headend architectures with a goal to reduce the complexity and increasing serviceability of the cable infrastructure. In particular, R-PHY implements the DOCSIS PHY functions on a remote node, Remote-PHY Device (RPD), while centralizing the MAC and higher layer network functions at the headend. Whereas, the R-MAC implements the DOCSIS PHY and MAC functions on a remote node, Remote-MACPHY Device (PMD), while centralizing the IP forwarding and higher layer network functions at the headend. Centralized DOCSIS functions for RPD and RMD can be implemented as a software on a virtualized entity either at the headend or cloud.

The critical aspect of CRAN and DCCAP in the time domain I/Q transport are the lower latency and higher data rate requirements on the optical fiber [565]. A constant high bit rate and low latency connection must be maintained constantly between baseband processing and radio node regardless of the user traffic. The analog RF signals must be transmitted and received at all times even when there is no user activity. For e.g., the passband signal with the cell broadcast information, reference or pilot tones must be transmitted always. Thus, I/Q samples of the RF passband must always be transported at the constant rate at all the times. Moreover, the requirements of an optical fiber increases linearly with increase in the number of nodes. Therefore, numerous techniques such as [566–569] have been proposed to enable the dynamic compression of RF I/Q samples for the effective transmissions over the optical fiber. However the compression techniques are lossy because of the quantization of RF signal reducing the sensitivity of the receiver in the upstream. Nevertheless, the data rate requirements between cloud and radio unit leads to the dedicated deployments of optical fiber connections and static allocations of resources for the CRAN and DCCAP. Functional split architectures [565, 570] transport the upper layer data to the radio unit such that the constraints on the optical connection are relaxed. However, the additional processing at the radio unit increases the complexity at the node as well as the flexibility of the infrastructure is reduced as compared to the traditional CRAN is due to the distributed implementation of split RAN functions.

3.1.3 Contributions and Organization

In this article, we primarily focus on the trade offs and benefits of the functional-split in both LTE and cable networks. In particular, we focus on the split-PHY architecture which implements the IFFT/FFT at the radio units of both LTE and cable networks. Towards this end, the main contributions of this article are as follows:

i) Overview and trade off discussions on the functional split and split-PHY architectures for both LTE and cable networks. Presented in Sec. 3.2.

ii) A novel cross-split interaction mechanism for remote caching and prefetching of QAM symbols to reduce the data rate required for the I/Q transmissions between cloud and radio unit, especially in the *downstream* direction while implementing the IFFT/FFT at the remote nodes. Presented in Sec. 3.3.

iii) A novel mechanism to commonly share the infrastructure resources among LTE and cable networks The discussion also includes the general timing analysis for interleaving multiple IFFT/FFT computations of LTE and cable on a single IFFT/FFT module. Presented in Sec. 3.4.

v) In the end, we present the evaluation of FFT sharing mechanism and mean packet delay performance evaluation of the radio unit which implements IFFT/FFT for the simultaneous LTE and cable operation in comparison to existing R-PHY technology. Presented in Sec. 3.5.

3.1.4 Related work

Checko et al. [571] has conducted the CRAN technology review which includes advantages, challenges, SDN/NFV applications, as well as the compression techniques for I/Q transport over the fronthaul network. A more detailed discussions on the internals of the BBU and RRU units has been discussed by Wu et al. in [572]. They show that cooperative signal processing in the CRAN achieves better spectral efficiency and improves utilization as compared to traditional networks. CRAN also provides a platform to provide computing services to the users through the access network. A comprehensive survey on Mobile Cloud Computing (MCC) in the area of CRAN has been conducted by Fernando et al. [573]. Fundamentals of the functional and protocol split uplink as well as the downlink and uplink compression techniques has been presented in [574]. The impact of overhead due to packatization on the data rate and latency of the fronthaul link while supporting various functional split in the CRAN has been presented in [575].

Miyamoto et al.in their wireless performance evaluation [576] claim that their proposed split-PHY architecture reduces the fronthaul bandwidth by up to 97% compared to traditional CRAN with the penalty of 2 dB SNR. However, their proposed split-PHY architecture requires specialized transceiver designs and optical transmission mechanisms which may increase the cost of CRAN deployments. In a typical RRH deployment scenario, several RRHs experience different load due to the independent channel qualities of the UEs reducing the overall load RRH. Therefore, especially when the higher functional splits are considered, all the RRHs connected to the CRAN would likely not result in the peak load. User specific traffic variation can provide the multiplexing opportunity and the impact of such multiplexing for the RRH deployments has been studied by Chang et al. [575]. Further to split-PHY, Nishihara et al. [577] have evaluated the performance of MACPHY-split where both MAC and PHY are implemented at the RRH. Their simulation results show that MACPHY-split approach reduces the bandwidth from 10 Gbps to 600 Mbps while supporting the multiplexing.

CRAN involve large number of RRH deployments which can potentially be the source of large power consumptions. Efforts to reduce the carbon foot print over the cellular networks supporting both CRAN as well as traditional deployments has been presented in [578–581]. Whereas the energy saving mechanism in the wireless networks has been presented in [582]. Stephen et al. [583] have designed an cache enabled OFDM resource allocation mechanism which saves the transmissions over the fronthaul link. However, the content has to be saved in parts marked with identifiers in the remote node In contrast to all the previous CRAN studies, we have considered the caching of resource elements at the RRH on the split-PHY architecture to reduce the data rate over the fronthaul link potentially saving the energy consumption when user data is not present.

Complementary to the wireless cellular networks HFC network provides the broadband access to the residential users. Bisdikian et al. [584] has presented the overview of initial designs and protocol mechanisms for the cable networks. As compared to the earlier designs, current and future broadband access networks extends the capabilities of connectivity to Gigabit speeds [585]. Even further, present cable networks can be designed to support cellular networks services as described in Gambini et al. [586, 587]. The economic benefits of infrastructure sharing between residential wired and cellular wireless networks has been identified in [588]. Additionally, economic benefits form the integration of LTE and DOCSIS has also been discussed in [589].

Articles [590–592] have demonstrated efficient transmissions of CPRI equivalent fronthaul data up to 256 Gbps using the optical bandwidth of 10 GHz, especially for supporting MIMO LTE applications. However, the proposed mechanism in the articles use specialized optical transmission with constant traffic over the optical link without allowing the possibility of multiplexing. In addition, we propose the novel remote caching and prefetching of QAM symbols, which saves the fiber transmissions. Especially, when there are no users, optical fiber connectivity can be effectively turned off to save the power or share the resources with other nodes. In comparison to most of the access networks, such as, macro base stations, DAS, femto cells, and HFC, the traditional macro base station backhauled through a microwave link at low traffic results in the most energy economical option [593]. As cable networks are one of the sources for growing carbon footprint in the Internet connectivity, there has been several studies proposed to address the issue such as [594–596].

3.2 BACKGROUND ON FUNCTIONAL SPLIT IN LTE AND CABLE NETWORKS

3.2.0.1 Downstream v/s Upstream

Upstream In the upstream direction the RRU receives the RF signal transmitted from the users. This analog passband signal is down converted to baseband and digitized for the transmission to BBU for baseband processing. Unlike the cable link in the traditional cellar network and antenna infrastructures, the CRAN connects the BBU and RRU with an digital optical fiber. The cable link adds significant attenuation to the upstream signal especially due to the low level of received signal from the devices. Whereas, the digital fiber does not constitute towards the attenuation loss as it carries the signal in the digital form. To note, an extreme care is needed at the RRUs for digitizing the uplink signal from the users as an additional loss cannot be afforded due to the low signal level of uplink RF signal at the RRU. For example, if the cable link accounts for 2 dB of loss and noise floor is −120dB, then the received signal at the RRU connected a BBU over cable link must be ≤ −118 dB for the successful detection, whereas the received signal can be ≤ −120 dB if the RRU is connected to a BBU through the digital fronthaul link, thus increasing the dynamic range of the system by 2 dB. Although Single Carrier Orthogonal Frequency Multiplexing (SC-OFDM) uplink modulation format is used in the typical deployments, the technology is advancing towards the uplink OFDM systems especially for the MIMO applications [597, 598]. Therefore, in the scope of this article we focus on the symmetrical OFDM systems in both upstream and downstream directions. In addition to the increased dynamic range, the processing of upstream for the detection and extraction of information from the RF uplink signals can be centrally processed at the cloud on the generic hardware, such as the general purpose processors.

Downstream In the downstream direction BBU sends the information to RRUs for the generation of passband signal to transmit over the physical antennas. The RRUs can easily set the transmit power level gain states for RF signals. As in the upstream direction, there is no significant difference in terms of signal generation or the dynamic range of the systems between cable and digital fronthaul links. Similar to the centralized processing of upstream at the cloud, the information is centrally processed on a generic hardware, such as the general purpose processors to generate the baseband downlink signals.

3.2.1 Functional Split in LTE

Figure 3.1 shows the traditional CRAN deployment in comparison conventional cellular deployments. A radio base station eNB of LTE protocol stack towards the UE can be functionally split and implemented flexibly over radio node and cloud seprated by a fronthaul link which is typically an optical fiber connectivity The tra-

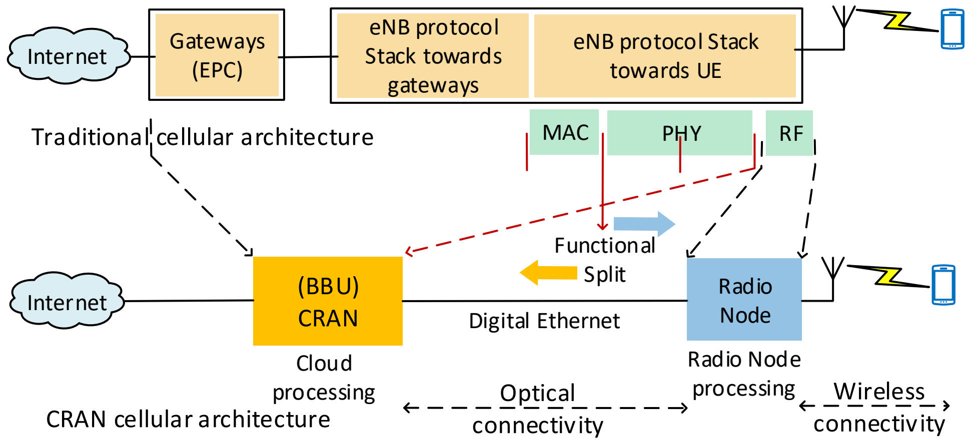


Figure 3.1: The Cloud-RAN (CRAN).

ditional CRAN transports the baseband time domain I/Q samples over the optical fiber to the RRUs. The number of RRUs that is supported over a fiber deployment depends on the amount of traffic that is required to support the operations of each RRU. Suppose if C is the capacity of the fronthaul optical connectivity and R_i is the data rate required by i^th RRU, then maximum number of RRUs N that can be supported over that specific fronthaul link is $\max_N\{\sum_{i=1}^{N} R_i\}$ such at $\sum_{i=1}^{N} R_i \leq C$. In the present deployments of CRAN the resources of the fronthaul link are statically allocated with dedicated connectivity. Therefore in symmetrical and homogeneous deployment, $R_1 = R_2 \ldots R_N = R$ resulting in the total number of RRUs that can be supported over the fronthaul link as $N = C/R$. The main bottleneck for the CRAN deployments is delay and capacity of the fronthaul link C. Heterogeneous fronthaul links where multiple RRUs requirements of delay and data rate changing over time independent of each other would require an advance resource management mechanisms to avoid the capacity wastages as compared to the worst case tolerance deployment practices. To understand the fronthaul requirements of an RRU, we estimate the data rate R required by the traditional CRAN where the baseband I/Q is transported from the cloud BBU to RRU for the most common LTE deployment scenarios. Table 3.1

Table 3.1: Typical LTE CRAN Parameters

Param.	**Description**	**Value**
N	Number of RRU per CRAN	1
B	LTE cell bandwidth	20 MHz
K	Bits per I/Q	10 bits
W	Number of Tx/Rx antennas	2
T_s	OFDM symbol duration	66.6 μs
f_s	Sampling frequency	30.72 MHz
f_c	Carrier frequency	2 GHz

summarizes the important list of parameters used for evaluation in the context of LTE for the fronthaul optical link connecting RRU to CRAN. The data rate comparisons of various functional split in the LTE protocol stack has been conducted in [565, 570]. In contrast, we take a closer look on the data rate requirements based on the implementation specifics of the protocol stack. That is, we track the flow of information across multiple protocol stack layers of the LTE and identify the key characteristics that dictate the requirements of fronthaul link.

Based on the computationally intensive operation of the FFT The data flow between BBU and RRU can be categorically divided into two types i) time domain samples and ii) frequency domain samples.

3.2.1.1 Time Domain I/Q Forwarding

The time domain I/Q samples represents the RF signal in the digital form either in the passband or baseband representation. Typically, the digital representation of the passband signal requires a very large data rate depending on the physical transmission frequency band. Thus, passband time domain I/Q forwarding is non economical. For example, in an LTE system, the passband signal is sampled at twice the carrier frequency f_c with each sample requiring 10 bits for digital representation, the passband I/Q data rate R_i^P required over the fronthaul link is

$$\begin{aligned} R_i^P &= N \times W \times 2 f_c \times 10 \\ &= 1 \times 2 \times 2(2 \times 10^9) \times 10 = 80 \text{ Gbps.} \end{aligned} \tag{3.1}$$

The baseband signal for an OFDM symbol in the time-domain consists time samples equal to the number of OFDM subcarriers because of the symmetric input and output samples from the IFFT/FFT structure. The cyclic prefix is added to the OFDM signal to avoid the inter symbol interference. In order to reduce the constraints on the RF signal generation at the RRU, the baseband signal is sampled at the frequency of 30.72 MHz with each sample requiring 10 bits for digital representation and an oversampling factor of 2, the baseband I/Q data rate R_i^B required over the fronthaul link is

$$\begin{aligned} R_i^B &= N \times W \times (2 \times f_s) \times (2 \times K) \\ &= 1 \times 2 \times (2 \times 30.72 \times 10^6) \times (2 \times 10) \\ &= 2.46 \text{ Gbps.} \end{aligned} \tag{3.2}$$

Although the data rate is significantly reduced as compared to the passband I/Q forwarding, the baseband I/Q data rate scales linearly with the number of antennas and bandwidth. Thus, for large number of antennas and larger aggregated bandwidth the data rate R_i^B can be very large.

3.2.1.2 Frequency Domain I/Q Forwarding

In the 20 MHz LTE system One OFDM symbol duration including the cyclic prefix is 71.3 μs which corresponds to 2192 samples. The useful symbol duration in OFDM is 66.7 μs of 2048 samples while the cyclic prefix duration is 4.7 μs of 144 samples. Thus, each of 2048 samples in the OFDM symbol (excluding the cyclic prefix) corresponds to 2048 subcarriers (B_{sub}) when transformed by the FFT. However, only 1200 of these subcarriers are used for signal transmission which corresponds to 100 resource blocks (RBs) of 12 subcarriers each the rest is zero-padded and serves as guard carriers. This leads to $(2048 - 1200)/2048 = 0.41 = 41$ % of unused guard carriers. Each subcarrier in the OFDM is modulated by a complex value mapped by a QAM alphabet. LTE QAM alphabet size is based on QAM bits such as, 64 QAM and 256 QAM. If only the subcarrier information which consists of the complex values taken from the QAM alphabet i.e., only the frequency domain data is used to transport between BBU to RRU. The resulting data rate R_i^F is only dependent on the number of subcarriers B_{sub}. A vector of complex valued QAM alphabet symbols of size B_{sub} needs to be sent once every OFDM symbol duration T_s i.e., the data rate

$$\begin{aligned} R_i^F &= N \times W \times B_{sub} \times T_s^{-1} \times (2 \times K) \\ &= 1 \times 2 \times 1200 \times (66.7 \times 10^{-6})^{-1} \times (2 \times 10) \\ &= 720 \text{ Mbps.} \end{aligned} \tag{3.3}$$

In comparison to time domain baseband I/Q data rate R_i^B, the R_i^F is approximately reduced by $(R_i^B - R_i^F)/R_i^B = (2460 - 720)/2460 = 70$ %. Further attempts to reduce the data rate R_i require moving complex functions, such as MAC to the RRU. The MAC HARQ (Hybrid ARQ) processes requires complex operations and large buffers to be implemented at the RRU increasing the complexity of the RRU. Thus, with the savings of 70 %, keeping the simplicity at the RRU is worthwhile to explore the transport mechanism of frequency domain I/Q symbols over the fronthaul link.

3.2.2 Functional Split in Cable Distributed Converged Cable Access Platform (DCCAP) Architectures

Traditional CCAP architecture for the HFC network implements the CMTS at the headend and transports analog optical signal to an Optical Remote Node (ORN) over the optical fiber. ORN then converts the optical analog signal to electrical RF signal

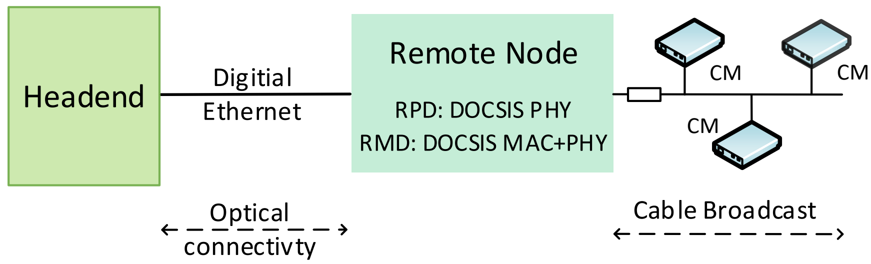


Figure 3.2: Distributed Converged Cable Access Platform (DCCAP).

to transmit over the cable segment. However, such architectures which rely on analog optics suffer from attenuation of the analog signal in both optical fiber segment as well as cable segment of the HFC network because of the placement of the ORN. If the ORN is deployed far from the headend, the attenuation in optical signal will be dominant, similarly if the ORN is deployed far from the CM (users) then the attenuation in the RF signal of the cable will be dominant. Modular Headend Architecture (MHA) overcomes the downside of CCAP architectures by enabling the functional splitting of CMTS allowing the modular implementation of the CMTS functions. Implementation of modular CMTS functions distributively across multiple nodes are referred to as Distributed Converged Cable Access Platform (DCCAP) Architecture. As shown in the Fig. 3.2 DCCAP architecture defines a new Remote Node (RN) which is connected to the headend through digital Ethernet fiber. Digital connection between the RN and headend eliminates the attenuation of the analog optical signal allowing the RN to be deployed more deeper into the users network reducing the cable segment length which in turn reduces the analog RF attenuation improving the overall Signal to Noise Ratio (SNR) at the CM. The network which connects the RN to headend is referred to as Converged Interconnect Network (CIN). MHA version 2 (MHAv2) [599] architecture defines two DCCAP architectures Remote-PHY and Remote-MACPHY.

3.2.2.1 Remote-PHY (R-PHY)

Overview In the R-PHY architecture, the DOCSIS PHY function in the CMTS protocol stack is implemented at the RN referred to as Remote-PHY Device (RPD), while all the higher layers in the CMTS protocol stack including the MAC as well as the upstream scheduler are implemented at the headend. A virtual-MAC (vMAC) entity virtualizes the DOCSIS MAC on a generic hardware which can be flexibly implemented either at the headend or cloud/remote data center. Since the upstream scheduler is implemented at the headend, the request from the CM is sent to the headend for processing the grants to coordinate the upstream transmissions over the cable link. The extensive performance evaluation of R-PHY and R-MACPHY have been conducted in [600, 601]. Therefore, the CM request-to-grant delay depends on the distance of RN from the headend (i.e., the CIN distance) [602, 603].

Advantages R-PHY node is simple to implement and hence the CAPEX and OPEX of the RPD can be reduced. At the headend, more computational resources can be dedicated to support the complex schedulers for mode advance coordination mechanism of CM transmissions over the broadcast cable medium.

Disadvantages As the distance of RPD from headend increase, the CM request-to-grant delay increases due to increases RTT between RPD and headend. Applications such as, virtual and augmented reality requires Ultra Low Latency (ULL) over the cable link can be impacted by the larger CM request-to-grant delays.

3.2.2.2 Remote-MACPHY (R-MACPHY)

Overview In the R-MACPHY architecture, the DOCSIS PHY and MAC functions along with the upstream scheduler in the CMTS protocol stack are implemented

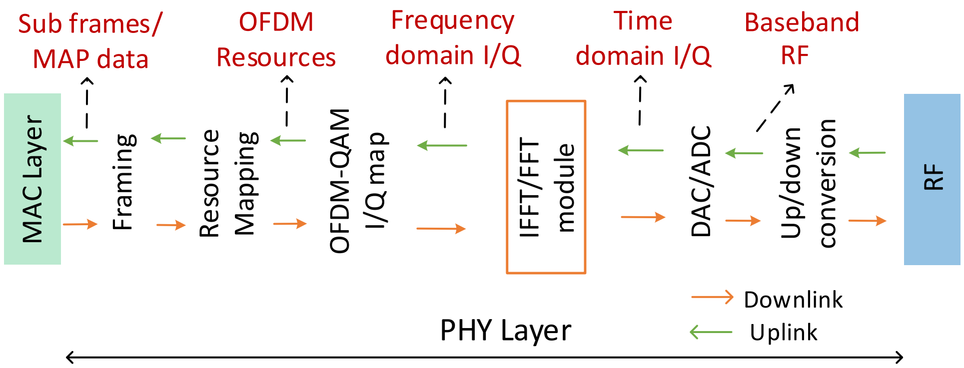


Figure 3.3: PHY-split architecture.

at the RN referred to as Remote-MAC Device (RMD), while all the higher layers in the CMTS protocol stack are implemented at the headend. Since the upstream scheduler is implemented at the RMD, the requests from the CMs are processed for the the grants at the RMD to coordinate the upstream transmissions over the cable link reducing the request-to-grant delay. Therefore, the CM request-to-grant delay is independent of the distance of RN from the headend.

Advantages R-MACPHY produces significantly lower delay when compared to R-PHY especially the CIN distance is very large. ULL applications can be readily supported as the upstream scheduler is implemented very close the CM reducing the request-to-grant delay.

Disadvantages RMD device has to implement the scheduler on the remote node increasing the CAPEX and OPEX of the remote node. As remote node implements more functions of the CMTS protocol stack in a distributed fashion, the flexibility of the network reduces as compared to centralized architectures, such as R-PHY.

3.2.3 Functional PHY-Split

The maximization of the âĂIJcloudificationâĂİ of CMTS DOCSIS and LTE functions results in the increased flexibility and reduced CAPEX and OPEX for the Multiple System Operators (MSOs) and cellular operators. The cloud implementation of DOCSIS and LTE functions can be easily achieved at the same physical location, remote data center or cloud. Both LTE and DOCSIS 3.1 also share similar transceiver PHY characteristics for the OFDM implementation that can be exploited to design the simultaneous support for LTE and DOCSIS over the HFC network which is critical to the 5G type of applications, such as health monitoring and security [604]. The general overview of the physical layer for LTE and DOCSIS is shown in the Fig. 3.3. In the downstream direction, the data from MAC layer is processed to PHY frames and mapped to OFDM resource locations which is then converted to frequency domain QAM I/Q symbols (see 3.2.1.2) based on the modulation and coding schemes. The QAM I/Q symbols are then IFFT transformed to get the complex time domain samples. This time domain samples (see 3.2.1.1) are then converted to analog RF signal for the transmission over the cable link. To note, the processing of I/Q information before the IFFT/FFT module is specific to DOCSIS and LTE protocol whereas the processing of I/Q after the IFFT/FFT module is relatively same for both DOCSIS and LTE. Thus, we can separate the functions based on the IFFT/FFT module such that IFFT/FFT is implemented at the remote node to support the the architectures and mechanisms to simultaneously operate LTE and DOCSIS over the HFC network. To the best of our knowledge, there exists no prior research for simultaneously supporting LTE and cable so as to efficiently utilize the optical fiber (fronthaul) resources of the already installed HFC plant.

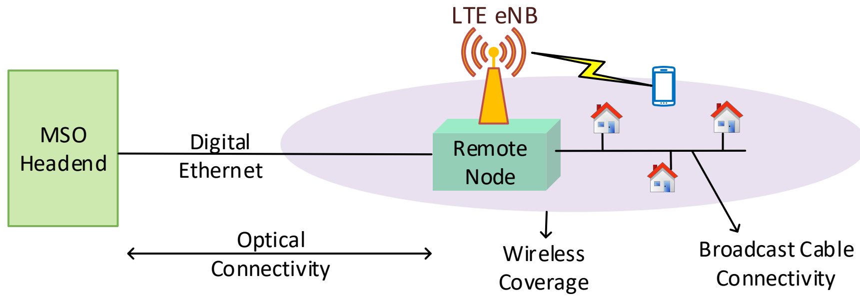


Figure 3.4: Deployment of the LTE eNB RRU at the Remote Node (RN).

3.3 PROPOSED CROSS-FUNCTIONAL SPLIT INTERACTION

The digital optical remote node (ORN) in the DCCAP architecture is deployed closer to the CM (users). Close proximity of the ORN to the residential subscribers would help in establishing the wireless LTE connectivity by deploying an LTE eNB RRU at the ORN site. As show in Fig. 3.4 installing an RRU at the ORN site is advantageous to the operators due to the close proximity of the users. With the establishment of LTE connectivity by the MSOs users can be wirelessly connected to the MSO's core network for the Internet connectivity increasing the service capabilities of the MSOs. In addition, support of LTE eNB RRU at the ORN also reuses the existing HFC infrastructure reducing the CAPEX and OPEX for the MSOs in providing the additional services of LTE.

Traditionally, the CRAN and DCCAP architectures split the functions linearly based on the protocol stack (i.e., MAC, PHY etc.), and implements the split parts at the ORN and cloud. Additional to protocol stack split, our proposed mechanism enables cross-split interaction through signalling to facilitate the caching and prefetching (see Sec 3.3.2) of redundant information between the functional splits. More specifically, cross-functional split interaction involves the communication of control information between baseband unit and radio unit.

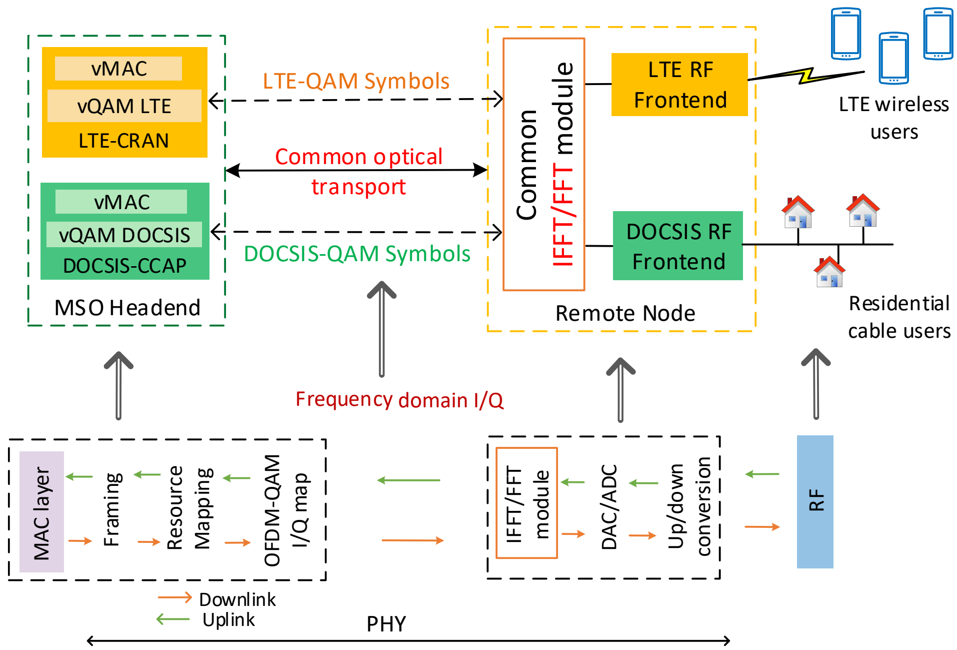


Figure 3.5: Remote FFT (R-FFT) implements the FFT module at the remote node.

3.3.1 Proposed Shared Remote-FFT (R-FFT) Node

In the uplink direction, the proposed remote node R-FFT converts the incoming DOCSIS RF signal from the CM to an encapsulated data bits format that can be transported over digital fiber link for additional processing and onward forwarding at the headend. In a similar way, for the downlink, RF signals are generated from the incoming formatted data bits and sent out on the RF link to the CMs. For LTE, an eNB can use a wide range of licensed spectrum with a single largest carrier component of 20 MHz, however the bandwidth can be extended further by carrier aggregation technique resulting in larger effective bandwidth. The R-FFT node effectively converts the upstream LTE RF signal from the wireless users and transports the signal digitally to the BBU/CRAN via the digital fiber link. In the downlink direction, the R-FFT node converts the digital information to an LTE RF signal that can be transmitted wirelessly to the users.

A Remote-DAC/ADC (R-DAC/ADC) would require peak rate transmissions [605]. Considering a system with a downlink bandwidth of 100 MHz and a 1024 QAM modulation format, which requires 12 bits per sample, results in a total bit rate over the fiber of (100 MHz) x (12) x (Frequency sampling rate). For a frequency sampling rate of 2.5 times (slightly greater than the Nyquist rate), the total required bit rate is 3 Gbps. In contrast, an equivalent R-PHY system requires a data rate of (100 MHz) x (10 Bits/Hz) x (90 %) = 900 Mbps; whereby, 100 MHz is for the resource allocation across the entire bandwidth, 10 Bits/Hz is for the 1024 QAM, and 90 % is for the effective channel with a 10 % guard band. This simple example comparison indicates a threefold increase of the data rate in the R-DAC/ADC system compared to the R-PHY system. Note that the R-DAC/ADC system requires a constant peak data rate to transport the I/Q samples, regardless of the amount of user data present in the RF signal. In contrast, similar to R-PHY/MAC, in R-FFT system, the data rate depends on the amount of user data. In the above example data rate calculation, we have considered the maximum allocation of the user data in the R-PHY system.

Our motivation is to address the increased fiber data rate through a balanced split among the functions within the PHY node, while keeping the simplicity of the R-DAC/ADC and the CRAN systems. The existing R-DAC/ADC node requires some digital circuitry, such as a CPU, for the DAC and ADC control. Therefore, we believe that the FFT/IFFT implementation is not a significant additional burden for the remote node [606]. Figure 3.5 shows the implementation of vMAC for both LTE and DOCSIS at the Headend and a common FFT module at the remote node. The advantages of proposed FFT implementation at the remote node include:

i) flexible deployment support for LTE and DOCSIS

ii) requires lower data rate (R_i^F) to transport frequency domain I/Q as compared to time-domain I/Q (R_i^B).

iii) data tones carrying no information are zero valued in the frequency I/Q samples effectively resulting a lower date-rate over the fiber channel in both LTE and DOCSIS with the chance for statistical multiplexing, and

iv) possible caching of repetitive frequency QAM I/Q samples, such as Reference Signals (RS) and pilot tones.

To emphasize the important data rate aspect, we note that in the proposed shared R-FFT, the data rate required over the fiber channel is directly proportional to the user traffic. We believe this is an important characteristic of the FFT functional-split whereby we can achieve multiplexing gains by combining multiple R-FFT nodes or by the enabling the concurrent support of LTE as illustrated in Fig. 3.4. With the similar characteristics of DOCSIS, the LTE user traffic also translates to proportional data rate over the fiber channel. In addition, the proposed mechanism enables the complex signal processing of the PHY layer to be implemented at the headend. Examples of the signal processing operations include channel estimation, equalization, and signal recovery, which can be implemented with general-purpose hardware and software. In addition, the processing of digital bits, such as the LDPC, which is necessary for the forward error correction, can also be implemented at the headend. Thus, the proposed approach reduces the cost of the remote nodes and increases the flexibility of changing the operational technologies. The software implementations at the headend can be easily upgraded while retaining the R-FFT node hardware since the node hardware consists only of common platform hardware, such as elementary DAC/ADC and FFT/IFFT components. Thus, the proposed approach eases the change/upgrade of technologies. That is, the R-FFT node has minimal impact on

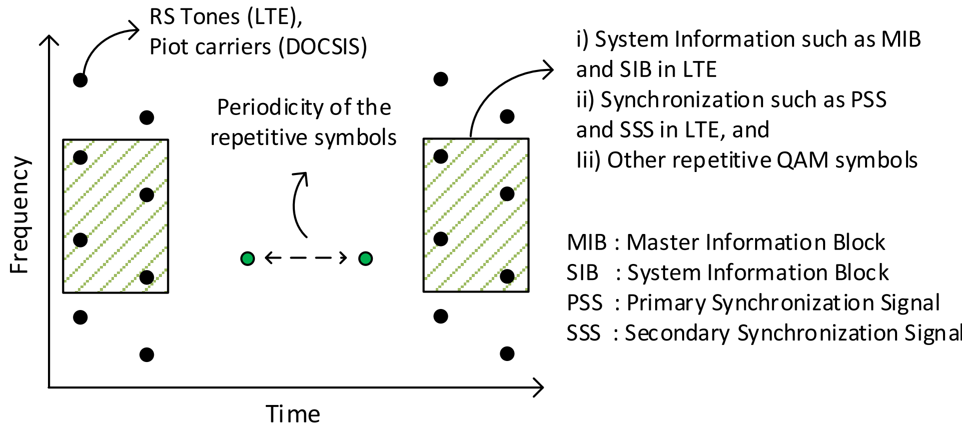


Figure 3.6: Caching at the remote node.

technology advancements because the blocks within a remote node are elementary or independent of most technology advancements.

3.3.2 Proposed Remote Caching and Prefetching

In order to further reduce the bandwidth in addition to functional split process, several techniques, such as I/Q compression [566, 567, 569, 607] can be employed. In contrast, we propose resource element (time and frequency slot) allocation based remote caching. If some part of the information is regularly and repeatedly sent over the interface, a higher (orchestration, in case of SDN) level of the signaling process can coordinate caching mechanisms. For example, there is no need to transmit the downlink I/Q samples of the pilot tones as they would remain constant in the DOCSIS. Figure 3.6 illustrates the overview of repetitive QAM symbols in the LTE and DOCSIS. There is a process of up-sampling and zero padding before and after the FFT/IFFT block, depending on the FFT size and the effective subcarriers, which can potentially be controlled and cached through the headend (depending on the implementation). Zero padded QAM symbols as well as certain reserved resource elements can be excluded from the transmissions while signaling the changes to the cache management at the R-FFT node. As compared to downstream, upstream information must be entirely transported to the headend to process all the signal component received by the R-FFT receiver.

3.3.2.1 LTE Networks

Reference Signal (RS) Tones Caching RS tones are the pilot subcarriers which are embedded throughout the operational bandwidth of the wireless system for the channel estimation to equalize the impairments of received wireless signal. Disturbances to the wireless signal are more prominent compared to propagation of signal in the wired channel and therefore the RS tones are added in close proximity with each other to accurately estimate the channel based on the channel characteristics, such as coherence-time and coherence-bandwidth. For a single antenna, the RS tones are typically spaced 6 subcarriers apart in frequency such that 8 RS tones exists in a single subframe, i.e, 14 OFDM symbols and single Resource Block (RB), i.e., 12 subcarriers of LTE. Thus, the overhead due to RS tones in the LTE resource grid is

$$\text{RS Overhead} = \frac{8}{12 \times 14} = 4.7\ \%. \tag{3.4}$$

Therefore, approximately 4.7 % of I/Q transmissions over the digital fiber can be saved from the RS tones caching at the remote node regardless of the system bandwidth.

PHY Broadcast Channel (PBCH) Caching PHY Broadcast Channel (PBCH) carries the Master Information Block (MIB) which is broadcasted continuously by the eNB regardless of the user connectivity. MIB includes the basic information about the LTE system such as the system bandwidth and control information specific to LTE channel. PBCH/MIB always uses central 6 RBs (i.e, 72 subcarriers) for the duration of 4 OFDM symbols to broadcast the MIB data. PBCH space in the resource grid is inclusive of the RS tones used in the calculation of Eq. 3.4 and therefore needs to subtracting while calculating the overhead for MIB transmission. PBCH/MIB occurs once every 40 ms and there exists 4 redundant versions of MIB which will be broadcasted with the offset of 10 ms. Thus, essentially PBCH/MIB occurs once in every 10 ms (radio frame). The PBCH/MIB overhead for the entire LTE system is

$$\text{PBCH Over.} = \frac{6 \times 12 \times 4 - (8 \times 6)}{1200 \times 14 \times 10} = 0.142\ \%. \tag{3.5}$$

Although 0.142 % is less, relative overhead of PBCH/MIB data increases significantly for lower bandwidth LTE system. Moreover, our evaluation of the PBCH overhead considers the full RBs i.e., 1200 subcarriers, 14 OFDM symbols and 10 subframes in the LTE. In a real system the allocation broadly varies user density i.e, generally only part of the RBs will be used increasing the overhead effects. For example, for a 1.4 MHz system (used in an IoT type of applications) with full RBs, the overhead jumps to

$$\text{PBCH Over.}_{1.4\text{MHz}} = \frac{6 \times 12 \times 4 - (8 \times 6)}{72 \times 14 \times 10} = 2.3\ \%. \tag{3.6}$$

Therefore, up to 2.3 % I/Q transmissions over the digital fiber can be saved from the PBCH/MIB caching at the remote node.

Synchronization Channel Caching Synchronization Channel (SCH) consists of Primary Synchronization Sequence (PSS) and Secondary Synchronization Sequence (SSS) which is broadcasted continuously by the eNB regardless of the user connectivity. PSS and SSS are the special sequence which helps in the cell synchronization of wireless users by identifying the physical cell ID and the frame boundaries of the LTE resource grid. PSS/SSS occurs every 5 ms (twice per radio frame) and uses central 6 RBs over 2 OFDM symbols. Similar to Eq. 3.5 and 3.6, the overhead due to PSS/SSS in 20 MHz and 1.4 MHz system is

$$\begin{aligned} \text{SCH Over.} &= \frac{6 \times 12 \times 4}{1200 \times 14 \times 10} = 0.171\ \%. \\ \text{SCH Over.}_{1.4\text{MHz}} &= \frac{6 \times 12 \times 4}{72 \times 14 \times 10} = 2.8\ \%. \end{aligned} \tag{3.7}$$

System Information Block (SIB) Caching In a similar way, the caching mechanism can also be extended to the System Information Blocks (SIBs) broadcast messages which is through the PHY Downlink Shared Channel (PDSCH) of the LTE. There are 13 different types of SIBs, from SIB1 to SIB13. SIB1 and SIB2 are mandatory broadcast messages while the transmission of other SIBs depends on the relation between the serving and neighbor cell configurations. On a typical deployment, SIB3 to SIB9 are configured and can be combined in a single message block for the resource block allocation. Typical configuration of the RB allocation type schedules the SIB over 8 RBs across 14 OFDM symbols in time (1 subframe) are used for the transmission of SIB1 and SIB2, and with the effective periodicity (with redundancy version transmission) of 2 radio frames (20 ms). The overhead and caching gain from the of SIB1 and SIB2 transmissions while subtracting the corresponding RS tones overhead 8×8, i.e., 8 tones per RB for 8 RBs is

$$\begin{aligned} \text{SIB Over.} &= \frac{8 \times 12 \times 14 - (8 \times 8)}{1200 \times 14 \times 20} = 0.381\ \%. \\ \text{SIB Over.}_{1.4\text{MHz}} &= \frac{8 \times 12 \times 14 - (8 \times 8)}{72 \times 14 \times 20} = 6.3\ \%. \end{aligned} \tag{3.8}$$

Caching of higher order SIBs i.e., from SIB3 to SIB 9 can achieve further savings, however, the resource allocation and periodicity can widely vary to accurately estimate the overhead.

The stationary resource elements across the time domain, such as SIB information is allowed to change over a larger time scale in terms of hours and days, at such times the cached elements are refreshed or re-cached through cache management and signalling procedures, see Sec. 3.3.3.1.

3.3.2.2 Cable Networks

In the DOCSIS 3.1 downstream pilot subcarriers are modulated by the CMTS with a predefined modulation pattern which is known to all the CMs to allow the interoperability. Two types of pilot patterns are defined in the DOCSIS 3.1 for OFDM time frequency grid allocations, i) continuous, and ii) scattered. In the continuous pilot pattern, the pilot tones with a predefined modulation occur at fixed frequencies in every symbol across time. Whereas, in the scattered pilot pattern, the pilot tones are sweeped to to occur at each frequency locations but at different symbols across time. The scattered pilot pattern has a periodicity of 128 OFDM symbols along the time dimension such that the pattern repeat for the next cycle. Scattered pilots assist in the channel estimation for the equalization process of demodulation. In a typical deployment [608], operational bandwidth is 192 MHz corresponding to the FFT size of 8K with the 25 kHz subcarrier spacing. The total number of subcarriers in a 192 MHz system is 7680 out of which there are 80 guard band subcarriers, 88 continuous pilot subcarriers and 60 scattered pilot subcarriers. Therefore, the overhead due to redundant subcarriers in the DOCSIS system which can be cached at the remote node is

$$\text{Cable Over.} = \frac{80 + 88 + 60}{7680} = 2.9\ \%. \tag{3.9}$$

3.3.3 Memory Requirements for Caching

Caching of frequency domain I/Q symbols in the OFDM comes at the cost of caching memory implementation at the remote node. Each I/Q symbol that needs to be cached is a complex number with real and imaginary part. For the purpose of evaluation, we consider each part of the complex number represented by 10 bits resulting in 20 bits in total for each frequency domain QAM symbol. The caching of RS tones in the LTE results in 4.7 % of the savings in the fronthaul transmissions as show in the Eq. 3.4. In the duration of each OFDM symbol, 2 RS tones exists for every 12 subcarriers. For the 20 MHz system, there would be 200 RS tones. Therefore, total memory required to cache the data of QAM symbols corresponding to the RS tones is

$$\text{RS Tones Mem.} = (2 \times 100) \times 2 \times 10 = 4000 \text{ bits.} \tag{3.10}$$

Similarly, caching of PBCH, SCH and SIB data requires

$$\begin{aligned} \text{PBCH Mem.} &= (4 \times 12 \times 6 - (8 \times 6)) \times 2 \times 10 \\ &= 4800 \text{ bits,} \\ \text{SCH Mem.} &= (6 \times 12 \times 4) \times 2 \times 10 = 5760 \text{ bits,} \\ \text{SIB Mem.} &= (8 \times 12 \times 14 - (8 \times 8)) \times 2 \times 10 \\ &= 5760 \text{ bits.} \end{aligned} \tag{3.11}$$

Whereas, for the DOCSIS, the the memory requirements for the caching of continuous and scattered pilots is

$$\text{Pilot Tones Mem.} = (80 + 88 + 60) \times 2 \times 10 = 4560 \text{ bits.} \tag{3.12}$$

Thus, based on Eqs. 3.4-3.9, total savings of approx. 7 % to 18 % can be achieved in the fronthaul transmissions when the full resource allocation over the entire bandwidth is considered in both LTE and DOCSIS. For lower allocations i.e, when there exists lesser user data, the caching process can achieve much larger relative benefits. In an extreme case, when the user data is not present, all the cell specific broadcast data information can be cached at the remote node such that the fronthaul transmissions can be seized reducing the power consumption. The total memory for the caching required at the remote node based on the Eqs. 3.11-3.12 is approximately 19120 bits. The implementation of cache at the remote node which is lesser than the size of 25 KB is relatively very simple and of no practical burden to the existing remote node. Therefore, we believe the savings of more than 7 % with almost negligible implementation burden is a significant benefit in the CRAN functional PHY-split.

3.3.3.1 Signalling and Cache Management

Signalling mechanism facilitates the cache management processes. Cache management operation involves, i) transporting the caching information to the remote nodes, ii) updating the cached information at the remote nodes with new information, and iii) establishing the rules for prefetching of cached resource elements at the remote node. Signalling agents at the headend/cloud and remote node coordinate with each other through a separate (i.e., non-I/Q transport) logical connection between headend/cloud and remote node. Some of the information which has been cached may change over time but at a larger timescale compared to the transmission of I/Q from headend to the cloud. The signalling overhead which arises from the cache management is negligible because of the timescale of signalling operations. Headend/cloud can notify the remote node with the changes through signalling to keep the information up to date at the remote node. Prefetching of the cached content has to be precisely executed with accurate placement of the subcarriers information in the particular time and frequency locations to an IFFT/FFT computational module.

3.3.4 Transport Networks and Protocols

3.3.4.1 Transport Networks

An R-FFT node can be connected to headend through variety of transport network solutions over the optical fiber connectivity as well as dedicated mmWave links. The fundamental requirement is to support the CRAN and CCAP demands while virtualizing the QAM functions at the headend. Some of the technologies that can be considered are:

Dark Fiber A fiber network that is deployed in excess of the existing requirement is referred to as a dark fiber network. Typically, dark fiber resources are abundant but with limited accessibility. If a headend can be connected to an R-FFT node using dark fiber, a large data rate with low latency connections can be established, supporting safe and reliable transport of required I/Q samples.

Optical Wavelength Division Multiplexing (WDM) WDM establishes end to end connectivity with the dedicated wavelength aggregated to meet the user demands. WDM with the potential to reach large data rates and low latencies can easily support the connectivity of the R-FFT with the headend.

Passive Optical Network (PON) A PON network typically provides high data rates in the Point to Multipoint Ethernet services for residential and Fiber to The Premises (FTTP) type of applications. If PON technology is used to establish the connectivity, careful latency limitations must be evaluated. Several interfaces, such as CPRI, exists to support the connections over the PON transport network.

Wireless A standard and dedicated microwave or millimeter-wave wireless links can support large data rate and low latency connection between two nodes. However, wireless links are limited by the range and sometimes require Line of Sight (LoS) operation.

3.3.4.2 Protocols

Protocol is required to coordinate the transmissions of I/Q data over the transport network. A strict latency requirement for the CRAN and DCCAP architectures limits the choice of generic protocols over Ethernet. Some of the fronthaul protocol that exists for the transport of information between headend/cloud and radio node are:

Radio over Fiber (RoF) Radio over fiber (RoF) transports the radio frequency signal over an optical fiber link by converting the electrically modulated signals to optical signal. RoF signals are not converted in frequency but superimposed over optical signals to achieve the benefits of optical transmissions, such as reduced sensitivity to noise and interference RoF signals are optically distributed to end nodes where the optical signals are directly converted to electrical signal with minimal processing reducing the cost of the remote node. The downside of the RoF is the analog transmission of the optical signal which attenuate over distance over the fiber as compared to the digital data over the fiber.

Common Public Radio Interface (CPRI) Common Public Radio Interface (CPRI) [609] defines the protocol to transport the digitized I/Q data through the encapsulated CPRI frames. As compared to RoF, CPRI provides more reliable end-to-end connection between headend/cloud and the remote node. Dedicated TDM channels can be established to supports multiple logical connections supporting different air interfaces. The downsides of the CPRI are the strict timing and synchronization requirement as well as support for only the fixed functional split to transport time domain I/Q samples. To overcome the fixed functional split in the eCPRI is being currently developed to support a new functional split with ten folds of decrease in the data rate requirement over the fronthaul link. In comparison to eCPRI and CPRI protocols, our proposal is an enhancement to the base protocols where the repeated I/Q can be cached when frequency I/Q samples are transported over the fronthaul link.

Open Base Station Architecture Initiative (OBSAI) Open Base Station Architecture Initiative (OBSAI) [610] is similar to CPRI in which the digitized time domain I/Q samples are transported over fronthaul interface. In contrast to CPRI, OBSAI interface is an IP based connection. A digital interface which is based on an IP logical connection can be implemented over any generic Ethernet link providing a flexible

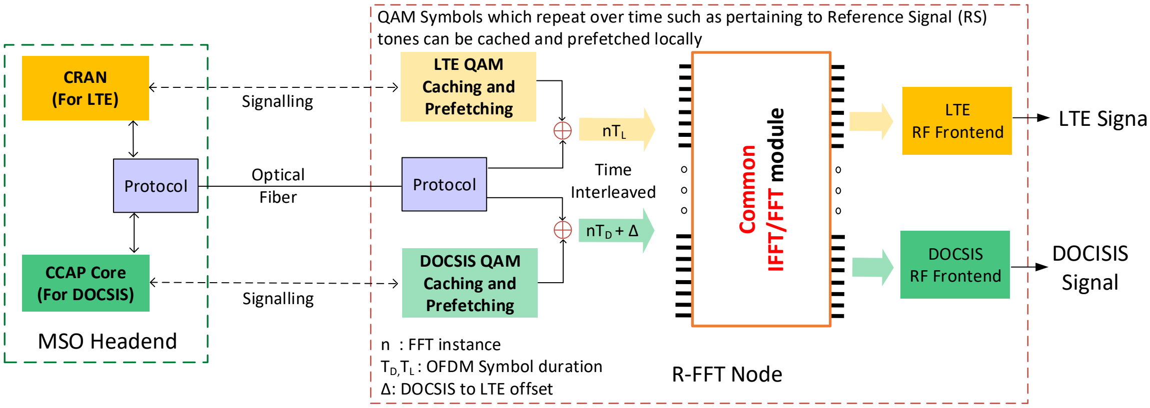


Figure 3.7: Reuse of infrastructure.

connectivity between headend/cloud to remote node.

External PHY Interfaces Downstream External PHY Interface (DEPI) [611] and Upstream External PHY Interface (UEPI) [612] enable the common transport mechanisms between R-PHY and CCAP core. DEPI and UEPI are based on the Layer 2 Tunneling Protocol version 3 (L2TPv3). The L2TPv3 transparently transports the Layer 2 protocols over a Layer 3 network creating the psedudowires (logical connections). For the R-MACPHY, since only the MAC payload is required to be transported to the headend for processing of upper layer data, strict requirements for the latency as in the case of R-PHY can be relaxed, allowing any generic tunneling protocol to be used between headend and R-MACPHY.

3.4 PROPOSED COMMON PLATFORM FOR LTE AND CABLE NETWORKS

The last hop connectivity to the user devices is typically enabled by wireless technologies. Although, any wireless interface, such as Bluetooth, ZigBee, or WiMax, can provide the wireless last hop connectivity, WiFi is a very promising technology. WiFi has proven to be simple and efficient for managing large numbers of connections as well as to serve large data rates to connected nodes. Also, importantly, WiFi has the capability of delivering high data rates (up to Gbps) in the unlicensed bands over a reasonable coverage area (up to 100 m), and in indoor environments. In contrast, the LTE wireless interface, which is widely used for commercial cellular communications in licensed bands, is capable of delivering up to several hundreds of Mbps over larger geographical areas (up to several tens of miles). Several efforts are underway to integrate these two wireless technologies so as to enable even higher data rates on the order of several Gbps. LTE-U and LTE-LAA [6] are newly developed wireless interfaces where a primary LTE link opportunistically utilizes the unlicensed WiFi bands. The next generation personal computers are expected to support LTE connectivity in conjunction with Ethernet and WLAN. However, to meet the future demands to support concurrent connectivity, deployment and management of independent LTE and WiFi technologies by the same operator incurs large expenses to the operators. We envision a solution where LTE base station can be established at the remote node in the DCCAP architecture. To our knowledge, the implementation of FFT at the remote node to simultaneously support cable and LTE infrastructure is novel to our proposal.

3.4.1 Common IFFT/FFT for LTE and DOCSIS

The protocol of LTE and DOCSIS share the same physical properties as they depend on OFDM for the physical layer modulation technique. Implementation of the OFDM is dependent on the design of FFT computations [613]. The property by which both LTE and DOCSIS require same IFFT/FFT operations to be performed for each OFDM modulation and demodulation can be exploited to reuse the existing infrastructure provided such mechanism can sustained on the computing hardware. Thus, the main motivation of the FFT implementation at the remote node is to bring out the common platform at the remote nodes while the transmission formats are flexibly realized at the headend for heterogeneous protocols based on OFDM. Figure 3.7 describe the internals of the R-FFT architecture simultaneously supporting cable and

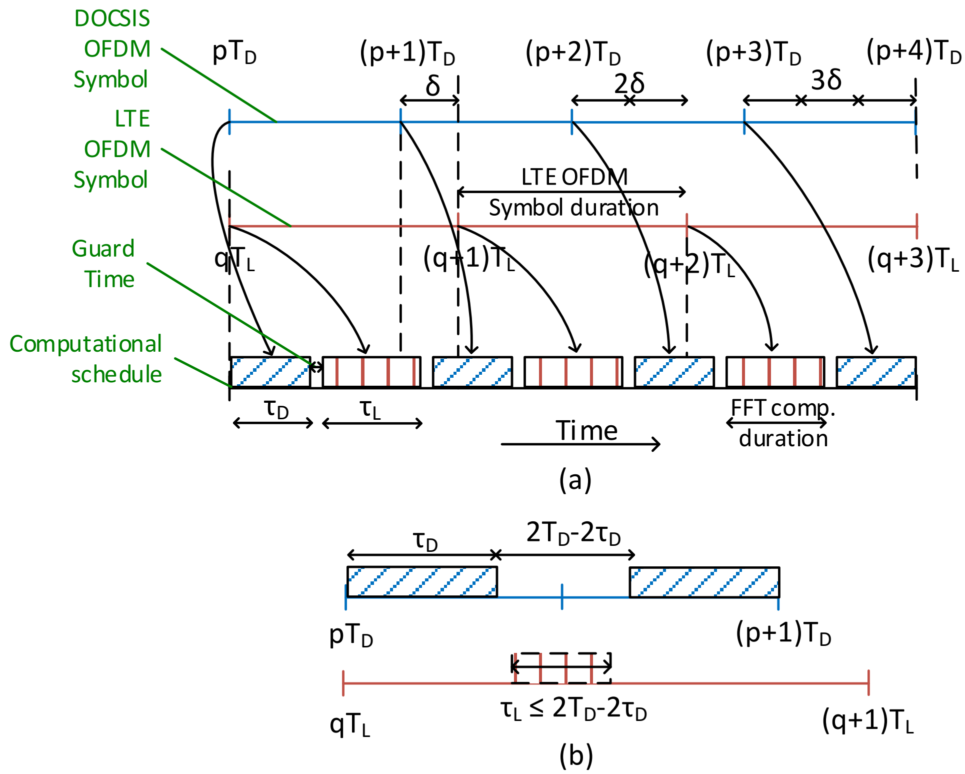


Figure 3.8: The IFFT/FFT interleaving.

LTE. Generally, in the downstream direction, an IFFT operation is performed once every OFDM symbol duration. The LTE OFDM symbol duration is approximately 72 Âţs, and for DOCSIS, the OFDM symbol duration is 84.13 Âţs. However, the actual time to compute IFFT can span from few microseconds to several tens of microsecond. Considering that there exists a large portion of idle time durations in the IFFT module during the FFT computation, we can interleave the I/Q input in time such that same IFFT/FFT module can be used for multiple technologies. By reusing the IFFT/FFT computing structures we can reduce the complexity of the hardware, be more power efficient, and reduce the cost of R-FFT node.

3.4.2 FFT Computations Interleaving Timing Discussion

In this section we preset the timing schedule analysis for the interleaving of IFFT/FFT computations on a single computing resource. Figure 3.8 shows the basic timing diagram to schedule the FFT computations on the computing resource. T_D and T_L are the OFDM symbol durations of DOCSIS and LTE respectively. Similarly, τ_D and τ_L are the durations of FFT computations for DOCSIS and LTE. While p and q are the timing indexes for the frame of reference for DOCSIS and LTE independent periodic events. WE also assume that T_L and T_D start at the time index p and q without any offset as show seen in the Fig. 3.8

For illustration, in this article we assume the OFDM symbol duration of LTE is greater then the symbol duration of DOCSIS, i.e., $T_L > T_D$, Consequently, the duration of FFT computations depends on the FFT size where we assume $\tau_D > \tau_L$, as DOCSIS has the larger FFT size compared to LTE. Also, it is most likely that heterogenous technologies operate with different OFDM symbol times. Thus, we define the difference in the OFDM symbol duration as $\delta = T_L - T_D$.

Feasibility Discussion Suppose if there is no offset between the cycles as shown in the start of timing schedule in Fig. 3.8 and k/l denotes the fraction of OFDM symbol durations, where, k and l if exists are the minimum positive integers, such that $T_L/T_D = k/l$, for every k cycles of T_D there would be l cycles of T_L. That is, when two periodic signal are overlapped, the difference of periodicities T_L and T_D, δ, at each cycle turns out to be integer multiple of the previous cycle. For example, in the Fig. 3.8 at the first cycle we define $\delta = T_L - T_D$, for the second cycle the difference is $2T_L - 2T_D = 2\delta$ and similarly for the third cycle the difference is 3δ. Since $T_L > T_D$ From the fundamental principles we can evaluate that after $k = \lceil T_L/\delta \rceil = \lceil T_L/(T_L - T_D) \rceil$

cycles of T_D, the overlapping behavior repeats. Also, the For example, in the Fig. 3.8, for every $k = 4$, which corresponds to 4 cycles of T_D and 3 cycles of T_L, the behavior repeats. Therefore, if the stability is ensured for k cycles of T_D or l cycles of T_L, the system is stable and feasible.

Thus, considering the larger OFDM symbol duration T_L as the reference, where we have l cycles of T_L for the secondary periodicity of combined k and l cycles. For the system to be stable, the total FFT computation durations from combined LTE and DOCSIS i.e., $l\tau_L + k\tau_D$ should not exceed the duration of l cycle of T_L i.e.,

$$l\tau_L + k\tau_D \leq lT_L. \tag{3.13}$$

We know that k cycles of T_D is equal to the l cycles of T_L, i.e., $kT_D = lT_L$ and therefore, $k = \frac{lT_L}{T_D}$. Substituting k in the Eq. 3.13 we get,

$$\begin{aligned} \left(\frac{lT_L}{T_D}\right)\tau_D + l\tau_L &\leq lT_L \\ \frac{T_L\tau_D}{T_D} + \tau_L &\leq T_L \\ \tau_D T_L + \tau_L T_D &\leq T_L T_D. \end{aligned} \tag{3.14}$$

In addition to Eq. 3.14, as shown in the Fig. 3.8 we need to ensure that FFT computation durations are sufficiently small to support the interleaving. That is, for interleaving $\tau_{\max(T_L,T_D)}$ on the periodic cycles of $\min(T_L, T_D)$, we need at least the space of

$$\tau_{\max(T_L,T_D)} \leq 2\min(T_L, T_D) - 2(\tau_{\min(T_L,T_D)}). \tag{3.15}$$

Constraints The end of each OFDM symbol duration marks the trigger point for the FFT computing scheduling request. Our fundamental analysis is based on the fact that IFFT/FFT computing takes much less time compared to the actual OFDM symbol duration, especially as the computing hardwares are becoming more advanced [614, 615]. As this factor is dependent on the hardware we impose following constraints to design the interleaving scheduling procedure of two heterogeneous technologies on the same hardware, i) the FFT computing durations should not exceed their OFDM symbol duration, and ii) the FFT computations must be finished before the start of next OFDM symbol, i.e.,

$$\begin{aligned} \tau_L &< T_L, \\ \tau_D &< T_D, \\ p\tau_L &< (p+1)T_L, \\ q\tau_D &< (q+1)T_D. \end{aligned} \tag{3.16}$$

Thus, in addition to Eq. 3.14, the constraints presented in the Eq. 3.16 must be satisfied in the process interleaving of computations to have no adverse effects on the operational technologies.

Effect of Guard Time Guard time separates two consecutive computations to compensate for the load and read time of the I/Q to the FFT structure while supporting the coexistence of two technologies on the same computation module. We define θ as the constant guard time which is applied to each scheduling set of the FFT computation. Based on Eq. 3.14, the impact of guard time can be evaluated as

$$(\tau_D + \theta)T_L + (\tau_L + \theta)T_D \leq T_D T_L, \tag{3.17}$$

which can be written as,

$$\tau_D T_L + \tau_L T_D \leq T_D T_L - \theta(T_L + T_D). \tag{3.18}$$

Implementation Sharing of remote node infrastructure for multiple technologies can be in both upstream and downstream, as the computations are performed independent of each other even for wireless full-duplex communications. The FFT computation

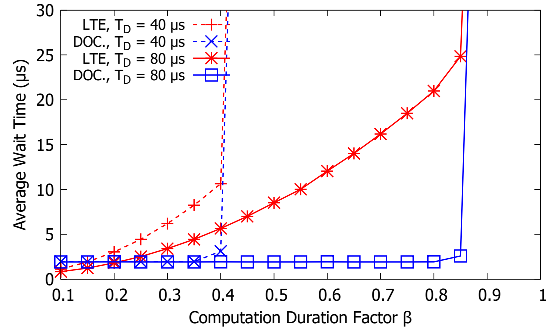
Algorithm 2: Caching and FFT Computation Procedure

1. CRAN/Headend
(a) Identify cachable I/Q samples.
(b) Create Caching rules.
(c) Signal the rules and data for caching.
if *Cached I/Q samples requires updating* **then**
  Signal remote node for cache renew or flush.
end
2. Remote Node
foreach *OFDM Symbol in* T_D *and* T_L **do**
  if *Caching is enabled* **then**
    Read cache and I/Q mapping;
    Insert I/Q cache-read to recieved I/Q;
  end
  if *FFT module is free* **then**
    Schedule I/Q for FFT based on Eqs. 3.13-3.16;
  end
  else
    Schedule at completion of current execution;
  end
end

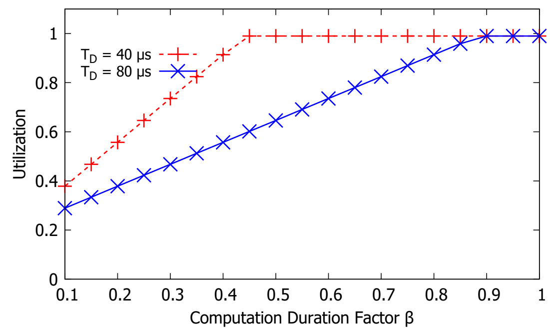
duration τ can be aggregate of multiple instances of OFDM symbol, for example, in the case of carrier aggregation in LTE (or channel bonding in DOCSIS), there would be an OFDM symbol for each carrier component resulting in $\tau_L = \tau_1 + \tau_2 \ldots \tau_C$, where C is the number of carrier components. Similarly, computations resulting from multiple LTE eNBs at a single node can be aggregated and abstracted to a single τ_L resulting in a lager τ_L can be very close the symbol duration T_L. Proposed approach can also be easily extended to more than two technologies which depend on FFT computations by sharing the the remote node.

3.5 PERFORMANCE EVALUATION

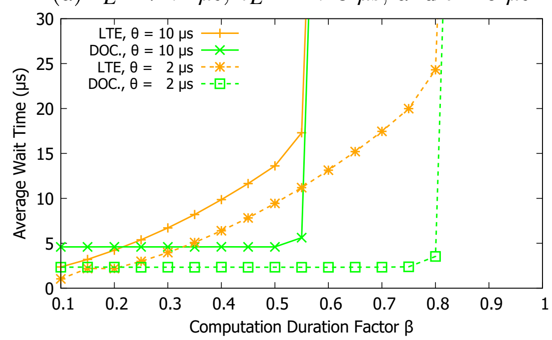
In this section we present the performance evaluation of the R-FFT node where the infrastructure of a remote node is shared for two independent LTE and DOCSIS technologies.



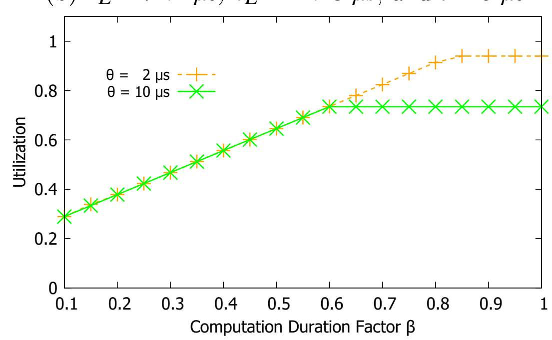
(a) T_L = 71.4 μs, τ_L = 14.28 μs, and θ = 0 μs



(b) T_L = 71.4 μs, τ_L = 14.28 μs, and θ = 0 μs



(c) T_L = 71.4 μs, τ_L = 14.28 μs, and T_D = 80 μs



(d) T_L = 71.4 μs, τ_L = 14.28 μs, and T_D = 80 μs

Figure 3.9: Simulation results for FFT interleaving procedure.

3.5.1 FFT Module Sharing

In the initial evaluation, we verify the proposed FFT interleaving procedure. we have implemented the FFT interleaving mechanism as a discreet event simulation framework in OMNET++. A LTE and DOCSIS OFDM symbols are generated every T_L and T_D durations respectively. For LTE with normal cyclic prefix the OFDM symbol duration T_L is 71.4 μs, while the DOCSIS symbol duration can be either 40 or 80 μs. For each OFDM symbol arrival at the radio node, FFT computation is queued by the scheduler. Typically, the FFT size for the LTE is 2K, whereas the FFT size for the DOCSIS can be 4K or 8K based on the symbol duration (i.e., 40 or 80 μs). Computation duration τ for the FFT computation can vary based on the number of carrier components and number of radio nodes supported by the remote node as described in Sec. 3. Interleaving procedure should be aware of the computation duration for each technology to ensure the stable operation of infrastructure sharing. To evaluate the system for wide range of FFT computation duration, we define a computation duration factor

$$\beta = \frac{\tau_L}{\tau_D}. \tag{3.19}$$

We choose the FFT computation duration τ_L to be 20 % of the T_L, which is $0.20 \times 71.432\ \mu s = 14.2832\ \mu s$ and the computation factor β is varied from 0 to 1 with an effective sweep of the FFT computation duration τ_D (i.e., $\min(T_L, T_D)$) from 0 to T_L, which is effectively $0 \leq \tau_D \leq T_L$. We primarily evaluate the FFT sharing mechanism with two performance metrics, average wait time and utilization. Average wait time is the average time required to schedule the FFT computation after the arrival of an OFDM symbol. Whereas, the utilization parameter is defined as the ratio of total computation time to total elapsed time.

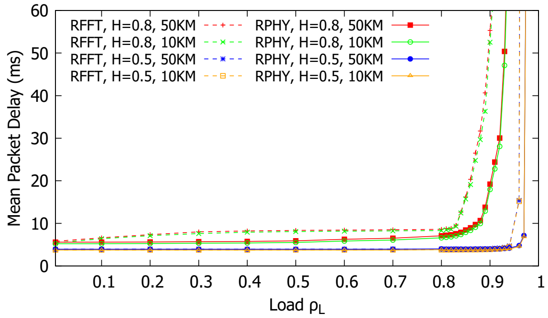
Figure. 3.9 presents the performance evaluation of proposed FFT sharing mechanism. Throughout the evaluation, the OFDM symbol duration of LTE is kept constant $T_L = 71.4\ \mu$s. Figure. 3.9(a) shows the average wait time of LTE and DOCSIS as a function of computation duration factor β for different values of DOCSIS OFDM symbol duration, $T_D = 40\mu$s and $T_D = 80\mu$s. We can observe from the Fig. 3.9(a), the average wait time of LTE increases linearly as the computation factor β is increased which corresponds to increase in the FFT computation duration of DOCSIS τ_D. This shows that the computation duration of one technology has the direct impact on the average wait time of another as they compete with each other for the computational resource. We also observe that the average wait time of both LTE and DOCSIS for $T_D = 40\ \mu$s linearly increases up to $\beta = 0.45$ and overshoots to a very large indicating the instability of the system. This is because, for the FFT computation sharing mechanism to be stable, the Eq. 3.14 must be satisfied, i.e, $\tau_D \leq (T_L T_D - \tau_L T_D)/T_L$, which is, $\tau_D \leq (40 \times 71.4 - 14.28 \times 40)/71.4 = 32\ \mu s$. When $\beta = 0.45$, the corresponding $\tau_D = 0.45 \times T_L = 0.45 \times 71.4\ \mu s = 32.13\ \mu s$, surpassing the stability limit based on Eq. 3.14, which is $> 32\ \mu s$. This behavior can also be observed in Fig. 3.9(b) which plots the utilization as a function of computation factor β. While the utilization of FFT computation module increases linear with β, the system approaches nearly 100% utilization when $\beta > 0.45$ for $T_D = 40\ \mu s$ reaching the stability limit of the system. Similarly, when the DOCSIS OFDM symbol duration T_D is changed from 40 μs to 80 μs, the behavior of average wait time is similar to $T_D = 40\ \mu s$, but the system becomes unstable when $\beta > 0.9$. When β is 0.9, the value of τ_D is $0.9 \times T_L = 0.9 \times 71.4\ \mu s = 64.26\ \mu s$, which is slightly greater than stability limit of $\tau_D \leq (80 \times 71.4 - 14.28 \times 80)/71.4$ or $\tau_D \leq 64\ \mu s$. Consequently, we can observe from Fig. 3.9(b), the utilization of system approaches to 100% for $\beta \geq 0.9$ for $T_D = 80\ \mu s$.

Fig. 3.9 (a) and (b) corresponds to the evaluation when guard time $\theta = 0\ \mu s$ for different values of DOCSIS OFDM symbol duration $T_D = 40$ and 80 μs. In contrast, Fig. 3.9 (c) and (d) evaluates the system for different guard times $\theta = 2$ and 10 μs for $T_D = 80\ \mu s$. Fig. 3.9 (c) plots the average wait time as a function of computation factor β, whereas, Fig. 3.9 (c) plots the system utilization as a function of β. Fig. 3.9 (c) shows the same behavior as in Fig. 3.9 (a), where the average wait time for LTE increases linearly as the β is increased. The scheduling of τ_D experiences a constant delay of 2.3 μs until the stability limit as the computation duration of LTE is retained constant in the simulation $\tau_L = 14.28\ \mu s$. In contrast to Fig. 3.9 (a), system reaches stability limit for lower values of β in (c) and this behavior pronounced as the guard time is increased. More specifically, when θ is increased from 0 (see Fig. 3.9 (a) for $T_D = 80\ \mu s$) to 2 μs, the system becomes unstable for $\beta = 0.85$ as compared to $\beta = 0.9$. Based on Eq. 3.18, for a system with guard time to be stable, $\tau_D T_L + \tau_L T_D \leq T_D T_L - \theta(T_L + T_D)$ or $\tau_L \leq (T_D T_L - \theta(T_L + T_D) - \tau_L T_D)/T_L$. When

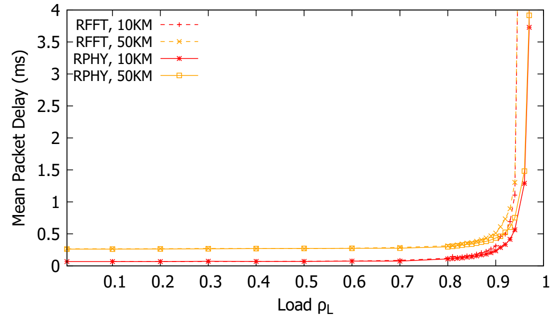
β = 0.85 which corresponds to τ_D = 60.69 μs, with θ = 2 μs, the stability condition evaluates to be $tau_D \leq 59.75$, therefore, the system is unstable for β = 0.85 indicated by the very large in the average wait time for $\beta > 0.85$. Similarly, for β = 0.6 which corresponds to τ_D = 42.84 μs, with θ = 10 μs, the stability condition evaluates to be $\tau_D \leq 42.79$, therefore, the system is unstable for β = 0.6. Additionally, the effect of guard time has the direct impact on the utilization of the system. We see from Fig. 3.9 (d), the maximum achievable utilization of the system is only up to 94 % when guard time θ = 2 μs for $\beta > 0.8369$. As value of $theta$ is increased to 10 μs, the maximum achievable utilization is reduced to 73.5% for $\beta > 0.59$. The saturation in the utilization also indicates the instability of the system, where the average wait time grows to a very large value for $\beta > 0.8369$ and $\beta > 0.59$, when guard time θ = 2 and 2 μs respectively.

3.5.2 End-to-End Delay Evaluation

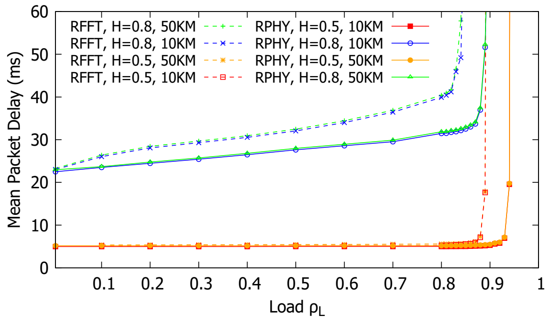
Subsequently, in this evaluation, we study the delay characteristics of R-FFT deployment in comparison to existing R-PHY deployments. In addition, we also present the impact of cable traffic on the LTE fronthaul link when the same cable infrastructure is shared between LTE and DOCSIS. We developed a simulation framework in a discreet event simulator OMNET++ to implement the DCCAP cable architecture of the HFC network. A remote node (RPHY or RFFT node) is connected to the headend through an optical connectivity separated by a distance d and data rate of R_o = 10 Gbps. 200 Cable Modems (CMs) are connected to the remote node through a analog broadcast cable connectivity. We assume the DOCSIS 3.1 protocol to coordinate the cable transmissions in the cable broadcast medium with the bidirectional cable data rate R_c = 1 Gbps. We implemented a Double Phase Polling (DPP) protocol[616] for the scheduling of 200 CMs over the cable segment. In case of RPHY, DOCSIS PHY frames are digitized and transported over Upstream External



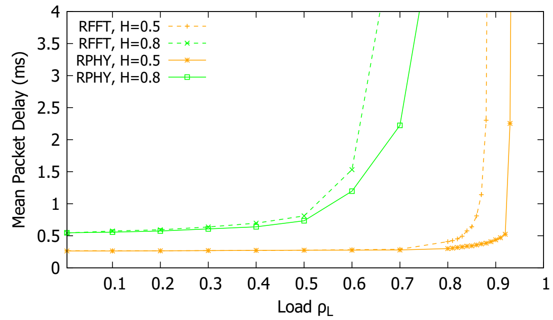
(a) DOCSIS Delay (end-to-end), $\rho_c = 0.2$



(b) LTE Delay (fronthaul), $\rho_c = 0.2$, $H = 0.5$



(c) DOCSIS Delay (end-to-end), $\rho_c = 0.6$



(d) LTE Delay (fronthaul), $\rho_c = 0.6$, $d = 50$ km

Figure 3.10: Simulation results for RFFT and RPHY.

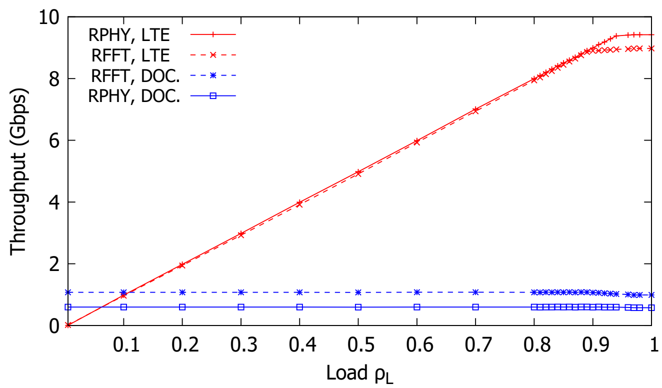


Figure 3.11: Average DOCSIS (cable) and LTE throughput.

PHY Interface (UEPI) where the REQ packets were prioritized. Whereas for the RFFT, the upstream cable data is converted to frequency I/Q and transported as a generic UDP packet. FFT size of $4K$ which corresponds to $T_D = 40$ μs and QAM size of 12 bits, and the code rate of 9/10 are used in the process of converting data to frequency domain I/Qs. Each complex number representing an I/Q symbol is digitized with 20 bits. We assume the deployment of an LTE RRH at the site of remote node in conjunction to the operation of RFFT or RPHY node sharing the optical connectivity of data rate R_o to the headend where the BBU CRAN is implemented. We note that our study is focused on deployment of LTE networks over the HFC cable infrastructures. Therefore, we implement and evaluate the performance of a cable network when an LTE fronthaul traffic is simultaneously injected to the shared optical link. We have modeled a typical FIFO queue at the remote node to froward the LTE packets to CRAN/BBU. We model the self similar traffic generation at each CM with varying burst levels controlled by the hurst parameter H with the average packet size of 472 KB. The hurst parameter $H = 0.5$ corresponds to the Poisson traffic, and the burstiness increases as the value H is increased.

Figure 3.10 presents the performance evaluation of the RFFT and RPHY network in presence of the LTE fronthaul traffic. In Fig. 3.10(a) we show the mean packet delay of the DOCSIS as a function of LTE fronthaul traffic intensity ρ_L which corresponds to the LTE data rate $R_L = \rho_L \times R_o$ for different optical distance d and traffic levels burstiness H, with fixed cable traffic intensity of $\rho_c = 0.2$ which corresponds to the traffic of $\rho_c \times R_c = 0.2 \times 1$ Gbps = 200 Mbps. Delay is considered for an end-to-end connection of the cable connectivity i.e., from the CM to headend. From Fig 3.10(a) we observe for the shorter optical distance which is typically deployed for an LTE fronthaul link has the minimal impact on the cable infrastructure for both RFFT and RPHY deployments. More specifically, for $H = 0.5$ in RFFT (and RPHY) for distance 10 km and 50 km we observe the delay difference of roughly 0.2 ms (delay of 3.73 ms for 10 km RFFT $H = 0.5$ and the delay of 3.93 ms for 50 km RFFT $H = 0.5$) when the distance is changed from 10 km to 50 km. This difference in the delay is from the propagation delay in the optical fiber which is approximately $(d_2 - d_1)/c = 40$ km$/2 \times 10^8$ m/s $= 0.2$ ms.

We also observe a minute difference in the delay between RPHY and RFFT implementation at the remote node for the Poisson traffic, but a larger difference for higher burstiness traffic. For example, at $\rho_L = 0.5$ we observe the mean packet delay values of 3.75 ms and 3.73 ms for RFFT and RPHY respectively. The difference in the delay of nearly 0.02 ms is due to the average transmission delay of the cable data which is inflated by the process of I/Q conversion and digitization. For the code rate of 9/10 and the QAM size of 12 bits the cable data would be inflated by factor of $(10/9) \times (1/12) \times 2 \times 10 = 1.85$. Thus, the RFFT packets undergo an additional delay at the remote node for the complete transmission of data to headend. However, this effect is pronounced for $H = 0.8$ because of the traffic with the higher burstiness. The behavior of the DOCSIS delay for RPHY and RFFT remains constant until $\rho_L = 0.96$ for $H = 0.5$ and $\rho_L = 0.8$ for $H = 0.8$, as the optical link is not congested. However for $\rho_L > 0.8$, the effective throughput over the optical link reaches more than the capacity R_o crossing the stability limit of the system. For e.g., the instantaneous cable traffic of RFFT on the optical link for $H = 0.5$ and $\rho_c = 0.2$ would be approximately 200 Mbps$\times$1.85 = 370 Mbps or 0.37 Gbps. Thus, when $\rho_L > 0.963$ the effective traffic would be more than R_o resulting in the very large value of delay due to instability of the system.

As seen in Fig. 3.10(b) which plots the mean packet delay for the LTE fronthaul traffic for RFFT and RPHY for different optical distances of 10 and 10 km. LTE fronthaul delay the directly impacted by deployed cable technology when the traffic from LTE and cable are aggregated at the remote node. RFFT induces more delay on the LTE fronthaul traffic compared to the RPHY, which is mainly resulting from the increase in the effective data rate over the optical link. Also, we can observe the effect of stability limit of the optical link which is in both Fig. 3.10(a) and (b) [see for e.g., the overshoot of the delay when $\rho_L = 0.96$ for RFFT, $H = 0.5$ and $d = 50$ km at

Fig. 3.10(a) and (b)]. Therefore, we can infer that RFFT and RPHY has the similar delay characteristics for cable traffic as well as the LTE fronthaul traffic.

To further study effect of cable traffic load, in Fig. 3.10(c) we evaluate the behavior of mean packet delay for DOCSIS when cable load is $\rho_c = 0.6$. Fig. 3.10(c) plots the mean packet delay as the function of LTE fronthaul traffic ρ_L. Similar to Fig. 3.10(a), we observe a narrow difference in the delay performance between RFFT and RPHY for the Poisson traffic ($H = 0.5$). But, for the self similar traffic with $H = 0.8$, we observe the difference of more than 10 ms between RFFT and RPHY which is partly due to the temporary cable link saturation resulting from the instantaneous load reaching more than the cable link capacity R_i ρ_c and 20 % which is reserved for cable maintenance. This difference is even further pronounced by the combined effect from the data inflation at the remote node. As the LTE fronthaul traffic ρ_L approach 0.8 and 0.94 for RFFT and RPHY respectively, the mean packet delay packet increases to a very large value resulted by the optical link saturation. For $\rho_c = 0.6$, the effective rate over the optical link is $\rho_L + (1.85 \times \rho_c)$, therefore, when $\rho_c = 0.6$, the optical link is saturated for $(1 - 1.85 \times 0.6) = 0.89$ which results in the large value of delay at $\rho_L = 0.8$ and 0.94 for RFFT and RPHY with $H = 0.5$. The throughput behavior is verified in Fig. 3.11 which plots the cable and LTE throughput as a function of LTE traffic intensity ρ_L. We can compare Fig. 3.10(c) and Fig. 3.11 to see that delay and the average throughput reaching stability at $\rho_L = 0.8$ and 0.94 for RFFT and RPHY with $H = 0.5$. On the other hand, when the distance is increased from 10 km to 50 km, we see the pronounced effect in delay difference between the RPHY and RFFT in Fig. 3.10(c). This effect is because of the combined impact of propagation delay and transmission delay due to data inflation of RFFT on the DOCSIS scheduler.

To understand the effect of traffic burstiness along with the cable load on the LTE fronthaul traffic, we show the mean packet delay as a function of LTE fronthaul traffic ρ_L in Fig. 3.10(d). We can relate the results in Fig. 3.10(c) to Fig. 3.10(d) as such the traffic with higher burstiness $H = 0.8$ increases delay of both cable and LTE fronthaul traffic. Additionally, the large fronthaul delay values at $\rho_L = 0.8$ and 0.94 indicates the stability limits for the Poisson traffic ($H = 0.5$) for RPHY and RFFT. However, the fronthaul delay is more impacted the higher burstiness ($H = 0.5$) as compared to the Poission traffic ($H = 0.8$) in the RFFT deployment. For example, even when the fronthaul load is $\rho_L = 0.5$ (i.e, below the stability limit), the fronthaul delay is almost increased by 4 times from 0.27 to 2.04 ms for $H = 0.8$ in the RFFT deployments. Therefore, if the functional split of LTE requires a dedicated QoS requirements, then a resource allocation mechanism of optical link may be employed for the dedicated assignments.

3.6 CONCLUSIONS

We have presented a mechanism for Time-Frequency resource elements (QAM) caching along with the FFT sharing for LTE and DOCSIS coexistence. We have comprehensively evaluated the FFT interleaving procedure through the simulation evaluation. Additionally we have also provided the performance comparison between the RFFT and RPHY remote nodes while coexisting with LTE networks. Our study numerically evaluate and show that RFFT performance is very close to RPHY. As RFFT achieves more flexibility and more scalability RFFT can be preferred for deployment. Additionally we also discuss the impact of functional split cable traffic on the LTE fronthaul traffic.

CHAPTER 4

FUTURE WORK OUTLINE: THE SDN-LAYBACK: AN SDN-BASED LAYERED BACKHAUL ARCHITECTURE FOR DENSE WIRELESS NETWORKS

4.1 INTRODUCTION

4.1.1 Need for a New Backhaul Architecture for Wireless Networks

A plethora of wireless devices running a wide range of applications connect to radio access networks (RANs), as illustrated in Figure 4.1. RANs provide end device to radio node (base station) connectivity. The radio nodes are connected to the core networks by technology-specific backhaul access networks, such as LTE or WiMax backhaul access networks. Present day hand-held wireless end devices have very high processing and memory capabilities, supporting various applications, including resource demanding ones such as live 4K video streaming. Advanced RANs, such as LTE-Advanced, support up to several hundred Mb/s in downstream by exploiting a range of physical wireless layer techniques, such as multi-carrier aggregation, opportunistic utilization of unlicensed bands, and millimeter wave technologies. A dense infrastructure of small cells with appropriate interference management is a critical technique for advanced RANs [617]. At the same time, the core networks already employ high-capacity optical links providing abundant transmission capacity.

However, the backhaul access networks have emerged as a critical bottleneck in wireless Internet access [618–621]. Today's backhaul access networks typically require highly-priced bulky network equipment with proprietary locked-in control software [121]. They also need to be highly reliable and have high availability. It is therefore very difficult to add new network functionalities, reconfigure operational states, or upgrade hardware as technology advances. These aspects have combined to stifle progress in backhaul access networks, causing them to become a critical bottleneck that can stall the progress of wireless networking and undermine the ad-

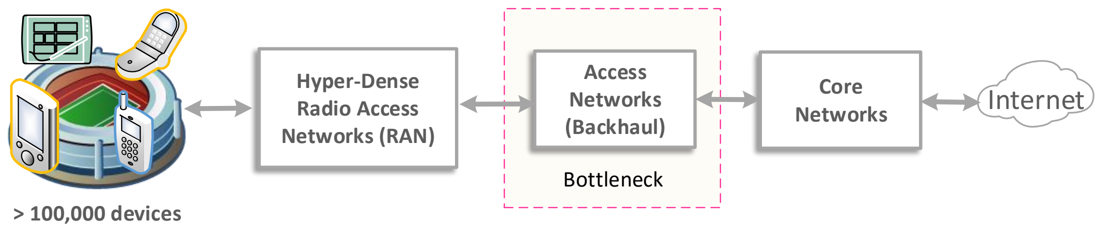


Figure 4.1: Bottleneck in the wireless Internet access chain.

vances in the complementary RANs and core networks. It can therefore be concluded that there is a need for innovative approaches, such as a new architecture, to enable technological progress in terms of backhaul access networks.

4.1.2 SDN-LayBack - an Advanced Wireless Network Backhaul Architecture

This paper proposes *SDN-LayBack, a fundamentally novel backhaul architecture for wireless backhaul access networks based on software defined networking (SDN)* [622, 623]. In contrast to other recently proposed backhaul architectures, such as CROWD [48], iJOIN [49], U-WN [50], and Xhaul [51], our SDN-LayBack architecture consistently decouples the wireless RAN technology (such as LTE or WiFi) from the backhaul access network. In addition, our SDN-LayBack architecture flexibly accommodates highly heterogeneous RANs, ranging from sparse cell deployments in rural areas to extremely high density cells in crowded stadiums. Further, to the best of our knowledge, SDN-LayBack is the first architecture to simultaneously provide a new clean-slate platform for cellular backhaul and support the coexistence with current cellular access backhaul technologies, such as LTE (4G/3G), WCDMA (3G), and GSM (2G). Previous clean-slate architecture proposals, such as the one proposed by Ameigeiras et al. [624], do *not* support existing cellular backhaul technologies, and hence have limited functionalities. SDN-LayBack is layered on top of the existing backhaul networks and flexibly supports a wide range of RANs through a network of

SDN switches and a hierarchical SDN controller pool.

This paper also introduces *an innovative four-step intra-LayBack handover protocol* within a given gateway in the SDN-LayBack architecture. Evaluations indicate 60 % reductions of the signalling load in comparison with conventional LTE handover. Finally, the article discusses future research directions within the SDN-LayBack architecture framework, focusing on interference mitigation, device-to-device (D2D) communication, and video streaming [625–632].

4.2 SDN-LAYBACK: A NOVEL SDN-BASED LAYERED BACKHAUL ARCHITECTURE

4.2.1 Overview

As already mentioned, the proposed SDN-LayBack is a novel SDN-based layered backhaul access network architecture which can be layered on top of an existing backhaul access network (e.g., SAE-3GPP-LTE) in an evolutionary manner. Fig. 4.2 illustrates SDN-LayBack's deployment on top of the classic LTE architecture.

Conventional backhaul access networks include technology-specific functional blocks for different RAN technologies. For instance, in the LTE architecture, macro cells are served by an LTE Serving-Gateway (S-GW), while pico/femto cells can be served by an Home-eNodeB-Gateway (HeNB-GW) (or S-GW), as illustrated in the bottom left of Fig. 4.2. RAN and backhaul are thus coupled in conventional wireless networks, e.g., a WiMax radio node cannot be used within an LTE architecture. Only with an additional dedicated network entity, an evolved packet data gateway (ePDG), can a WiFi radio node be connected to LTE backhaul with IPSec tunneling, as illustrated in the bottom middle of Fig. 4.2.

In contrast, our proposed SDN-LayBack architecture decouples the RAN from the backhaul, as illustrated in Fig. 4.2. The figure also indicates SDN-LayBack's four

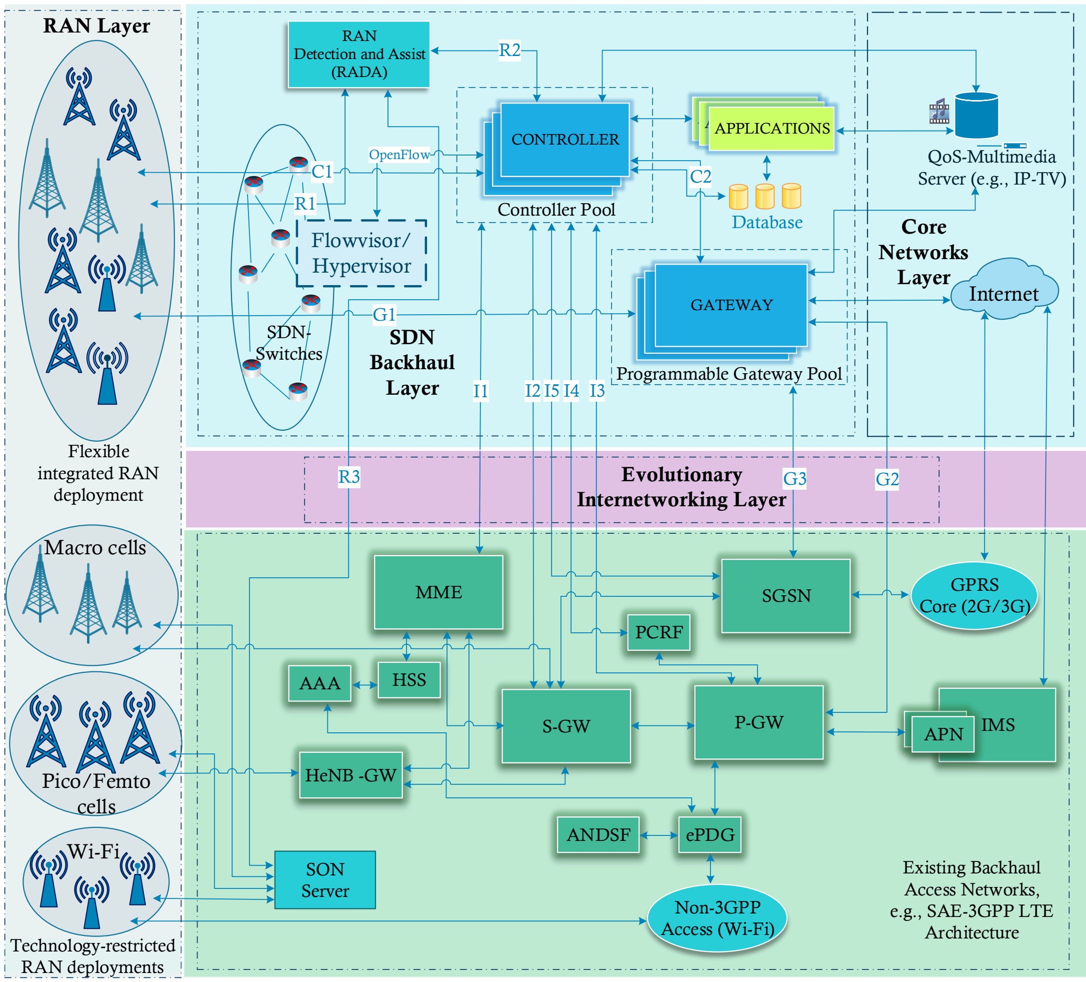


Figure 4.2: SDN-LayBack architecture.

architectural layers: *RAN Layer*, *SDN Backhaul Layer*, *Core Networks Layer*, and *Evolutionary Internetworking Layer*.

In the SDN-LayBack architecture, heterogeneous RAN technologies, such as LTE eNBs, pico/femto LTE, WiFi, and WiMax, can be flexibly deployed and accommodated in the *RAN Layer*. The *RAN Layer* interacts with the *SDN-LayBack Backhaul Layer* through the network of flexible SDN (OpenFlow, OF) switches and onwards through the programmable gateway pool to the Internet with the *Core*

Networks Layer. The data plane of the SDN-LayBack backhaul network consists of the network of SDN switches and the gateway pool. This data plane is centrally controlled by the SDN controller pool and the applications (with corresponding databases). SDN-LayBack interfaces with the classic backhaul access network architecture through *the Evolutionary Internetworking Layer*.

4.2.2 Outline of Layers in SDN-LayBack Architecture

This section outlines the key components and functionalities of the proposed LayBack architecture and contrasts the LayBack architecture with previous designs.

4.2.2.1 Radio Access Network (RAN) Layer

Wireless End Devices Mobile wireless end devices are heterogeneous and have a wide range of requirements. Providing reasonable quality-oriented services to every device on the network is a key challenge to the wireless network design. The proposed SDN-LayBack architecture takes a unique approach to provide requirement-specific network connectivity to every device that is connected to the SDN-LayBack network. Future devices will likely be highly application-specific, such as a speed sensor on a race track or a health monitoring biosensor. The SDN-LayBack architecture is designed to be adaptive to the different environments, such as an air port terminal, public park, or university/school. This enables SDN-LayBack to support a wide range of device requirements, such as real-time D2D video streaming at a large sporting event or music concert.

Radio Nodes Radio nodes, such as the evolved NodeB (eNB) in LTE or an access point (AP) in WiFi, provide RAN services to the end devices. Aside from LTE and WiFi, there exists a wide range of wireless access technologies (and protocols), including WiMax, Zig-Bee, Bluetooth, and near field communication (NFC). These wireless protocols have unique advantages and serve unique purposes. A fluidly flexible backhaul that homogeneously supports multiple different types of radio nodes does not yet exist, but is highly desirable. Therefore, our SDN-LayBack architecture is fundamentally designed to work with multiple RAN and communication technologies by isolating the RAN layer from the backhaul network.

In existing backhaul access networks, a given RAN technology requires a corresponding specific backhaul. For instance, the LTE radio access network can only operate with LTE backhaul network entities. This restriction of specific RAN technologies to specific backhaul technologies limits the usage of other RAN technologies on LTE backhaul networks and vice-versa. In addition, femto cells are expected to operate on multiple RAN technologies [633]. To address this restrictive structure of present RAN-backhaul inter-networking, we propose our SDN-LayBack architecture to flexibly support multiple types of radio nodes, including software defined radios integrated with SDN enabled radio nodes. In an interesting approach, the reconfigurable antennas [634–640] can be also be further extended SDN to achieve more flexibility in the RAN design.

Moreover, the system modeling for the RAN can be borrowed from the control literature. Techniques to design the systems for multiple specifications have been extensively discussed in [641–645]. Optimization problems can be formulated that address multiple objectives subject to constraints, by exploiting convex optimization ideas. Problems on a set of nonlinear hybrid systems, involving mixed-integer problems, can be solved using convexification [646]. High fidelity numerical simulators and system identification techniques can be used to efficiently solve optimization problems [647] using SDN.

4.2.2.2 SDN Backhaul Layer

The SDN backhaul layer encompasses the SDN switches (with hypervisor), a controller pool, and a gateway pool, as well as the applications and corresponding databases. Next, the main aspects of the SDN switches, controller pool, applications, and gateways are briefly outlined in this section.

SDN (OpenFlow) Switches SDN capable switches are today typically based on the OpenFlow (OF) protocol and are therefore sometimes referred to as OpenFlow switches or OF switches. We present SDN-LayBack in the context of OpenFlow switches, but emphasize that the SDN-LayBack architecture applies to any type of SDN-capable switch. OF-switches are capable of a wide range of functions, such as forwarding a packet to any port, duplicating a packet on multiple ports, modifying the content inside a packet, or dropping the packet. The switches can be connected in a mesh to allow disjoint flow paths for load balancing.

Controller Pool The SDN-LayBack controller pool configures the entire OF-switch fabric (network of OF switches) by adding flow table entries on every switch. The controller pool is also able to dynamically configure and program the gateway pool functions, such as queuing policies, caching, buffering, charging, as well as QoS [36, 37] and IP assignment for the end devices. The SDN-LayBack controller pool coordinates with existing (legacy) cellular network entities, such as the mobility management entity (MME) and other 3GPP entities, to coexist with present architectures. Connections from the SDN-LayBack controller to the 3GPP entities can be provided by extending the existing tunneling interfaces at the 3GPP entities. We define extensions of the tunneling interfaces as a part of the *Evolutionary Internetworking Layer* in Fig. 4.2. Thus, the proposed SDN-LayBack architecture can enable communication between, the new flexible RAN architecture in the top left of Fig. 4.2 as well as legacy technology-specific RAN and backhaul networks, see bottom of Fig. 4.2.

Applications Applications are programs executed by the controller for delegating instructions to individual SDN switches. The controller applications realize all the network functions required for Internet connectivity, such as authentication and policy enforcement, through the switch flows. Radio nodes require RAN-specific interfaces for their operation (e.g., the X2 interface in LTE), We realize these interfaces through controller applications on the network of SDN-switches. Therefore, for LTE in SDN-LayBack, eNBs are enabled with inter-radio node X2 interfaces along with other required interfaces. Cellular networks have many network functions, such as the Automatic Network Discovery and Selection Function (ANDSF) of 3GPP. As an example, to replace ANDSF in LayBack, a dedicated controller application will be responsible for delegating network access policies to the devices. Databases assist the SDN controller applications in their operations.

Gateways Gateway functions are programmed by the SDN controller to perform multiple network functionalities in order to simultaneously establish connectivity to heterogeneous RANs, such as LTE, Wi-Fi, and Wi-Max. For example, the gateway in SDN-LayBack functions as both S-GW and P-GW for an LTE radio node.

4.2.3 SDN-LayBack Hierarchical Micro-Architectures

The SDN-LayBack architecture can provide a wide range of heterogeneous services to localized regions through hierarchical SDN-LayBack micro-architectures. A micro-architecture hierarchy consists of a global (root) controller and multiple environment-specific local controllers located in the respective environments, as illustrated in Fig. 4.3. The local controllers can tailor applications for a specific environment, e.g., a

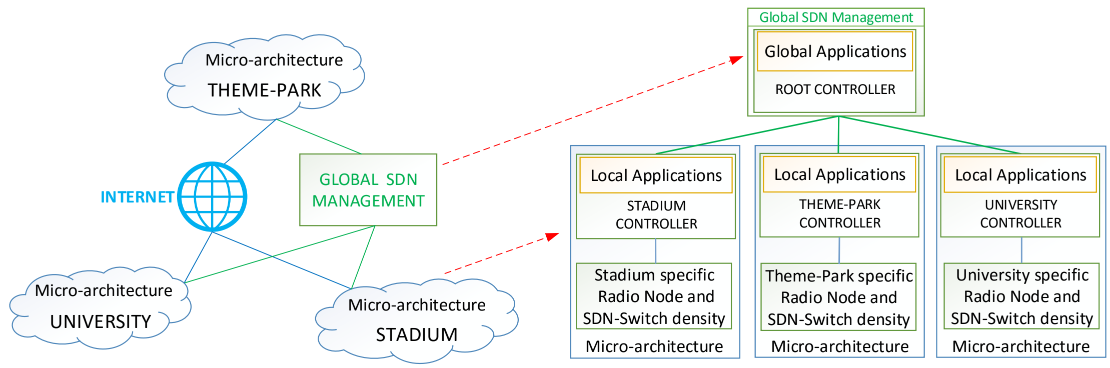


Figure 4.3: Environment-specific micro-architectures and controller hierarchy.

park with a sparse user population that may be located adjacent to a stadium with a very high user density. Accordingly, micro-architectures allow to classify applications specific to an environment as local applications and more common applications as global applications. For example, WiFi offloading and adaptive video streaming can be considered as local applications, whereas applications that serve a larger purpose, such as interference management, can be considered as global applications.

4.3 INTRA-LAYBACK HANDOVER: A RADICALLY SIMPLIFIED HANDOVER PROTOCOL

4.3.1 Motivation: Signalling Load Due to Frequent Handovers

The LTE protocol has generally higher signalling overhead compared to legacy 3G protocols. A recent forecast from Oracle Corp. [648] expects a large increase of the global LTE signalling traffic, which is predicted to surpass the total global IP traffic growth by 2019. The increase of signalling traffic can result in service interruptions to customers and financial losses to cellular operators. Therefore, new architectures with simplified signalling mechanisms are necessary to tackle the growth of signalling in the cellular networks.

Signalling in the cellular backhaul is required for a wide range of actions, in-

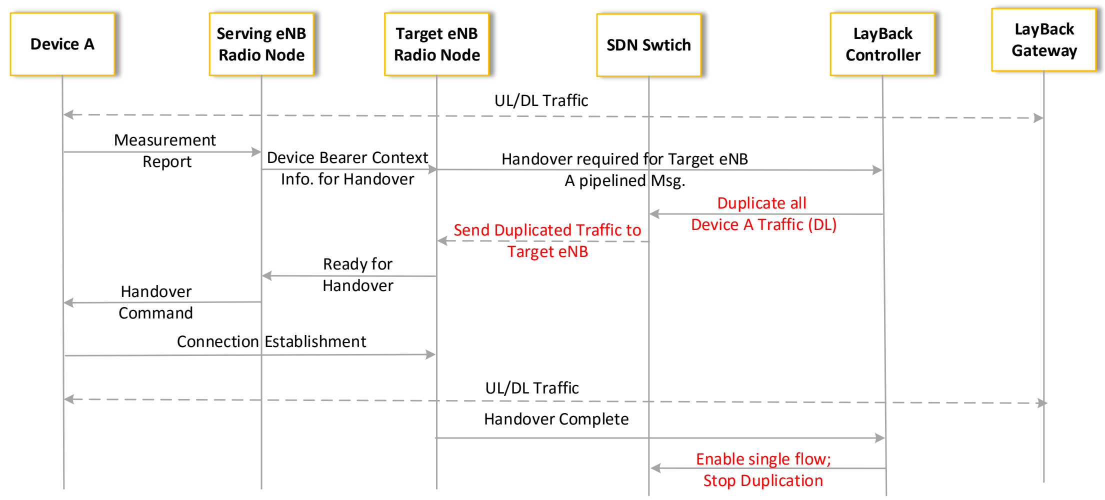


Figure 4.4: Proposed simplified intra-LayBack handover protocol.

cluding initial attach and handovers. Initial attach procedures are completed only when a device requests connectivity for the very first time. The initial attach procedure can result in large signalling overhead; however, it is executed only once. Handovers are initiated when a device measures and reports poor signal quality to the network. Depending on the configuration, the neighboring cell signal quality along with the quality of serving cell signal may be considered for handover decisions. Handovers require large amounts of signalling in the backhaul and occur very frequently. Especially in ultra dense networks (UDNs), where the cell range is reduced to relatively small areas on the order of several meters (e.g., 20 m in femto cells), handovers are very frequent. Even slow movements of devices can cause device moves between multiple cells, resulting in handovers. Hence, especially in UDNs, handovers are the source of serious bottlenecks in the backhaul entities.

4.3.2 Proposed 4-Step Intra-LayBack Handover

We propose *Intra Lay-Back Handover*, as the first mechanism to exploit the traffic duplication property of SDN to radically simplify the handover procedure in cellular backhaul. In comparison to X2 based LTE handover *within* the same S-GW, our proposed method for handover within the same LayBack gateway (Intra-LayBack Handover) achieves: 1) 100% reduction of the signalling load at the gateway, i.e., completely eliminates the handover signalling load on the LTE gateways, 2) 69% reduction of signalling load compared to the LTE MME, and 3) 60% reduction in the overall signalling cost.

We employ four steps in the handover protocol, as illustrated in Figure 4.4.

Step 1 Handover Preparation

When a measurement report satisfying the handover conditions arrives at the serving eNB (SeNB), the device bearer context information is forwarded to the target eNB (TeNB) and a message requesting handover is sent from the SeNB to the SDN-LayBack controller.

Step 2 Enable Traffic Duplication

LayBack controllers enable the traffic duplication at the SDN switch through an OpenFlow message for all the downlink traffic related to the device waiting to be handed over. The SDN switch continuously changes the headers (tunnel IDs) such that traffic related to the device reaches at TeNB. The bearer information pertaining to the device which has already been received by the TeNB from the SeNB is used to receive the duplicated traffic at the TeNB. Once the duplicated traffic related the device is received at the TeNB, a message is sent to the SeNB indicating the readiness for the handover. The SeNB then sends a handover command to the device (i.e., RRC reconfiguration in LTE).

Step 3 Perform Wireless Handover

Upon receiving the handover command, the device breaks the current wireless

Spec.	**Description** (SeNB – Serving eNB, TeNB – Target eNB)		**Signalling Cost**		**LTE GW Load**		**LayBack Load**	
	LTE (X2 based HO *within* same S-GW)	**LayBack** (same gateway)	**LTE**	**LayBack**	**MME**	**P/S-GW**	**Controller**	**Gateway**
TS 36 423	Handover Request (prep.), SeNB to TeNB	Handover Request (Bearer Info), SeNB to TeNB	1	1	0	0	0	0
	Handover Request ACK (prep.), TeNB to SeNB	Not Required	1	0	0	0	0	0
	Forwarding of Data, SeNB to TeNB	Not Required	1	0	0	0	0	0
TS 36 413	Handover Required, SeNB to MME	Handover Required, SeNB to Controller (Pipelined)	1	1	1	0	1	0
	Handover Command, MME to SeNB	OpenFlow Msg. Dup. Traffic, Controller to Switch	1	1	1	0	1	0
	Handover Request, MME to TeNB	Not Required	1	0	1	0	0	0
	Handover Request ACK, TeNB to MME	Not Required	1	0	1	0	0	0
	Not Required	Ready for Handover, HO Req. ACK , TeNB to SeNB	0	1	0	0	0	0
	Handover Notify (UE arrival), TeNB to MME	Handover Notify (UE arrival), TeNB to Controller	1	1	1	0	1	0
	Path Switch Req., TeNB to MME	Not Required	1	0	1	0	0	0
TS 23.401	Modify Bearer Request, MME to S-GW	Not Required	1	0	1	1	0	0
	Modify Bearer Request, S-GW to P-GW	Not Required	1	0	0	1	0	0
	Modify Bearer Response, P-GW to S-GW	Not Required	1	0	0	1	0	0
	Modify Bearer Response, S-GW to MME	Not Required	1	0	1	1	0	0
	Path Switch Req. ACK, MME to TeNB	Not Required	1	0	1	0	0	0
	Release Resource, TeNB to SeNB	OpenFlow Msg. Stop Dup., Controller to Switch	1	1	0	0	1	0
		Total Cost	**15**	**6**	**9**	**4**	**4**	**0**

Figure 4.5: Handover cost and load comparison in LayBack and LTE backhaul

link (a hard handover) and establishes a new wireless connection to the TeNB (through reserved RACH preambles in LTE) [649–652]. By then, duplicated traffic arrived prior to wireless connection reestablishment is waiting to be forwarded to the device in the new connection. Downlink traffic is then forwarded to the device as soon as the wireless connection is established.

Step 4 Stop Traffic Duplication

When the device traffic flow path through the new wireless connection is successful in both the uplink and downlink, then the TeNB sends a handover complete message to the LayBack controller. The controller sends an OpenFlow message to the SDN switch to stop the duplication by disabling the device traffic flow to the SeNB.

Other handover types, such as inter-LayBack gateway handover between different LayBack gateways, can be accomplished through extensions of the presented intra-LayBack handover.

4.3.3 Signalling Overhead Evaluation

Table 4.5 characterizes the amount of required signalling messages for X2-based handovers in LTE and for intra-LayBack handovers within the same gateway. We observe from Table 4.5 that the overall signalling cost is reduced from 15 messages in LTE to 6 messages in the proposed intra-LayBack handover, a 60 % reduction of signalling overhead. We note that we count an OpenFlow message sent from the controller to an SDN switch as a signalling message in this evaluation. We further observe from Table 4.5 that the load of processing 9 handover signalling messages at the MME in LTE is reduced to processing 4 handover signalling messages at the controller in LayBack. Moreover, the P/S-GWs in LTE need to process 4 signalling messages for a handover, whereas the LayBack gateway is completely oblivious to the handover mechanism. That is, the LayBack handover completely eliminates the handover signalling load on the gateway.

The LTE handover changes the bearers (UE context) on the gateway, requiring overall a high handover signalling load, whereby large signalling loads have to be processed at the LTE MME and P/S-GW. In contrast, the LayBack handover reduces the overall signalling load and employs the SDN switches to change the packet flow path. Essentially, the LayBack handover moves the handover burden from the gateway to the network SDN switches. The SDN switches can share the handover burden, avoiding bottlenecks.

4.4 SUMMARY AND FUTURE DIRECTIONS

4.4.1 Summary of SDN-LayBack Architecture and Handover Protocol

We have introduced SDN-LayBack, a novel layered backhaul architecture for wireless networks. SDN-LayBack consistently decouples the radio access networks (RANs) from the backhaul, permitting the flexible backhauling of highly heterogeneous RANs. Within the SDN-LayBack architectural framework, we have introduced a first protocol mechanism, namely a 4-step handover protocol for handovers within the scope of an SDN-LayBack gateway. The proposed LayBack handover mechanism relieves the signalling bottleneck at the backhaul gateways (e.g., LTE S-GW and P-GW) by (a) traffic duplication at SDN switches, and (b) bearer information forwarding from the currently serving eNB to the target eNB. Moreover, the LayBack handover reduces the signalling load on the backhaul control entities (e.g., MME) by (a) reducing the required signalling messages, and (b) moving some of the signalling messages from mobility control entities to the SDN controller. Our comparison of the handover signalling load indicates that LayBack achieves a 60 % reduction of the overall handover signalling load compared to the conventional LTE handover. Moreover, LayBack completely avoids handover processing at the gateway and distributes the handover processing load over a network of SDN switches, avoiding processing bottlenecks.

4.4.2 Future Direction: Interference Management Protocol

There are many exciting avenues for future protocol developments and evaluations within the SDN-LayBack architectural framework. Since interference is one of the main limitations for the deployment of small cells, an important future research direction is to exploit the capabilities of the SDN-LayBack architecture for interference mitigation protocols. We can exploit the central control (with a global holistic perspective) in SDN-LayBack for coordinating the long-term wireless configurations, such as center frequency, bandwidth, and time-sharing patterns, as well as protocol-specific configurations (e.g., random access channel parameters in LTE). We emphasize that the goal of SDN-LayBack interference management would *not* be to manage the physical resources, such as sub-frame power control in LTE, at the micro level. Instead, SDN-LayBack interference management assigns high-level configurations in a coordinated manner to the radio nodes so as to mitigate interference.

4.4.3 Future Direction: D2D Communication Protocol

Device-to-Device (D2D) communication will likely play an important role in the future of real-time content sharing and is another promising direction for SDN-LayBack protocol development. The LayBack architecture can be exploited for D2D communication so as to avoid flooding on the access network. More specifically, the SDN controller can maintain a subscriber (location) data base to coordinate the connection establishment and routing between D2D communication partners.

4.4.4 Future Direction: Video Streaming Protocol

Another direction is to develop and evaluate collaborative video streaming protocols within the micro-architecture framework (Section 4.2.3) of SDN-LayBack. For densely populated areas, e.g., airport terminals and stadiums, it is highly likely that multiple RAN technologies, e.g., LTE and WiFi, are deployed, and multiple simultaneous (unicast) video streams are being transmitted to (or from) devices within the coverage area of the considered micro-architecture, which is controlled by a local controller. A LayBack video streaming protocol can exploit the multiple ongoing video streams and multiple RANs to collaboratively trade off the video traffic characteristics (e.g., traffic bursts from complex video scenes) with RAN transmission conditions to achieve improved video experience across an ensemble of video streams. In addition to existing techniques such [653–658] can be applied to the SDN LayBack framework.

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