AMERICAN UNIVERSITY OF BEIRUT

Tactile-capable Optical Cloud Distribution Networks

by

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A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Computer Science
to the Department of Computer Science
of the Faculty of Arts and Sciences
at the American University of Beirut

Beirut, Lebanon
February 2018

AMERICAN UNIVERSITY OF BEIRUT

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Date of thesis defense: February 8, 2018

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Acknowledgements

First and Foremost, I give thanks to God for the wisdom, strength, and ability to finish this research.

I would like to express my sincere gratitude to my thesis advisor, Prof. Ahmad R. Dhaini, for his motivation, patience, and continuous support throughout this research work. His expert guidance, immense knowledge, and tenacious dedication to excellence have helped me during all times to accomplish my thesis.

Next, I would like to thank the rest of my thesis committee: Prof. Wassim El Hajj and Prof. Haidar Safa, for their insightful comments on this thesis.

Also, I must thank the American University of Beirut University Research Board (URB) for sponsoring this research.

I thank the Department of Computer Science at the American University of Beirut for making it possible for me to study here by offering me a Graduate Assistantship.

I take this opportunity to record my sincere thanks to my parents, my sister, my uncles Elie and Charles, and my grandmother Mariam, for their unfailing support and endless love throughout my life and through the time of my research.

I express my profound gratitude to my loving grandfather Edward who took the lead to heaven before the completion of this work.

Last but not least, I would like to thank my best friend Maria Hindy for keeping me in her prayers and remaining a true friend of mine for thirteen years now. Also, my warmest thanks go to my great friend Maher Daher whose non-stop support and encouragement was worth more than I can express on paper.

An Abstract of the Thesis of

Joelle Edward Neaime for Master of Science
Major: Computer Science

Title: Tactile-capable Optical Cloud Distribution Networks

Over the past decade, Cloud computing has become the most beneficiary paradigm to provide optimized and efficient computing resources for modern Internet applications. However, cloud networks can be a burden for latency-sensitive applications, such as Tactile Internet, which can't afford the high delay due to communication with remote cloud servers, which typically reside in the core network. In this work, we propose OCLDN, an agile, programmable and scalable Optical CLoud Distribution Network, which exploits content distribution networks, to deliver killer cloud and tactile services to end-users at very high-speeds, ultra-low latency, and low cost. With OCLDN, a software defined networking (SDN)-based mini-cloud data center is installed at the central office of a next-generation passive optical network, which includes a cloud-based tactile steering server, and supports all types of cloud applications. Meeting the stringent quality-of-service (QoS) requirements for these applications requires a

fast, adaptive and effective bandwidth allocation mechanism. We mathematically formulate this problem using Mixed Integer Linear Programming (MILP), and then introduce a new Dynamic Wavelength and Bandwidth Allocation (DWBA) scheme to overcome the limitations of the MILP model. The proposed DWBA scheme enables the protection of tactile services by dedicating it upstream wavelength(s), and enables inter-channel statistical multiplexing so as to maximize the network throughput without impairing the QoS requirements for all types of services. It also employs a modified version of the Water-Filling technique and advanced intra-ONU scheduling. Extensive simulations are performed; results demonstrate the ability of the proposed DWBA to outperform existing schemes, and highlight its effectiveness in meeting the QoS demands for all types of services.

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Chapter 1

Introduction

Over the last decade, Cloud computing has been employed as the killer technology for offering dynamically scalable infrastructure to modern Internet applications. In recent years, this revolutionary paradigm has gained a lot of popularity, with forecasts predicting that by year 2020, 92% of workloads will be processed by cloud data centers [8]. However, cloud networks may be a setback for some emerging ground-braking applications, such as Tactile Internet and Internet of Things (IoT). Due to the strict delay requirements of these latency-sensitive applications, significant delays resulting from the long distances between the end-users and cloud servers (which typically reside in the core network) can't be tolerated. Recent studies reported that applications running on cloud computing systems run up to 20% more efficiently when the data needed is located nearby [9]. As such, bringing the cloud resources closer to the end-users' premises is a fundamental need to support applications that are expected to reshape our society with their great potential impact. Several efforts have been spent to address this issue. For instance, Edge computing, or Fog Computing as termed by Cisco, has been recently presented as a very promising remedy, whereby the Fog (which is a Cloud closer to the ground) deploys fog nodes near the IoT end-user applications [10]. However, research in this field is still in its infancy stage with many challenges to be addressed before the technology is ready for deployment. Meanwhile, Internet service providers (ISPs) have been already serving a similar purpose by deploying content delivery networks (CDNs) extensively in their infrastructure in order to efficiently utilize their network resources and create a new source of revenues [11]. Therefore, it would be a promising and natural solution to combine these two exciting technologies so as to construct cloud distribution networks.

1.1 Contributions of the Thesis

In this work, we propose OCLDN, a high-speed, programmable, and scalable Optical Cloud Distribution Network architecture that enables ISPs to offer low-latency cloud services to the end users, by taking advantage of the next-generation Ethernet passive optical network (NG-EPON) technology [12], which has been a promising candidate for future high-speed cloud access networks [13, 14]. The NG-EPON technology is suitable for supporting the centralized hub-and-spoke-based traffic patterns of future enterprise local area networks [15]. With OCLDN, the ISP's CDN would deploy a mini-data center located at the central office (CO) to allow the end users' requests to be directly and quickly served by the mini-data center, and if need be, the data is fetched from the core servers [16].

One distinguished feature of OCLDN is its ability to support machine-to-human (M2H), machine-to-machine (M2M) and machine-to-cloud Tactile applications by deploying the control steering servers in the CO's cloud. Tactile Internet enables the transmission of touch and actuation in real-time, thereby enabling precise haptic communications through real-time interactive systems [17].

Several design requirements have to be met by the infrastructure supporting Tactile Internet; these include ultra-low latency (round-trip latency of 1 ms), reliability, security, high network availability [18]. All these require efficient resource management mechanisms with effective quality of service (QoS)-aware bandwidth allocation [19]. Thus, we formulate the scheduling and bandwidth allocation problem mathematically as a Mixed-Integer Linear Programming (MILP) problem. We then propose a new dynamic wavelength and bandwidth allocation (DWBA) scheme to address the limitations of the proposed MILP model, which is NP-Complete and does not scale well. The proposed DWBA scheme enables the protection of tactile services by dedicating it upstream wavelength(s), and is further enhanced to exploit inter-channel statistical multiplexing so as to maximize the network throughput without impairing the QoS requirements for all types of services. Our results show the ability of the proposed DWBA to outperform existing schemes, and highlight its effectiveness in meeting the QoS demands for all types of services.

1.2 Organization of the Thesis

The rest of the thesis is organized as follows. In Chapter 2, we present an overview of Passive Optical Network, Cloud Computing, Tactile Internet, and CDNs, along with relevant up-to-date related work. In Chapter 3, we describe the proposed OCLDN architecture and discuss its constituents, as well as the newly enabled services. In Chapter 4, we present the mathematical formulation and the new DWBA scheme. In Chapter 5, we present our simulation results; and finally in Chapter 6, we conclude our work and discuss future extensions.

Chapter 2

Background and Related Work

2.1 Passive Optical Network

Over the past two decades, the Internet has witnessed an explosive growth of data traffic and unprecedented emergence of a variety of broadband applications, including Voice over Internet Protocol (VoIP), Video on Demand (VoD), Internet Protocol Television (IPTV), High-Definition Television (HDTV), and interactive online gaming. As such, an ever-increasing demand for network bandwidth has been imposed on the underlying telecommunications infrastructure. To meet this challenge, backbone networks have experienced huge enhancements to provide high-capacity links that meet the demands of bandwidth-hungry applications. However, the access network, also known as the "last mile", has not been fully upgraded to meet the continuously fuelled bandwidth demands. Subsequently, it has become the bottleneck between the high-capacity residential/business end-users' local area networks and the backbone network. To alleviate this bottleneck, broadband access network operators must find an effective solution that increases

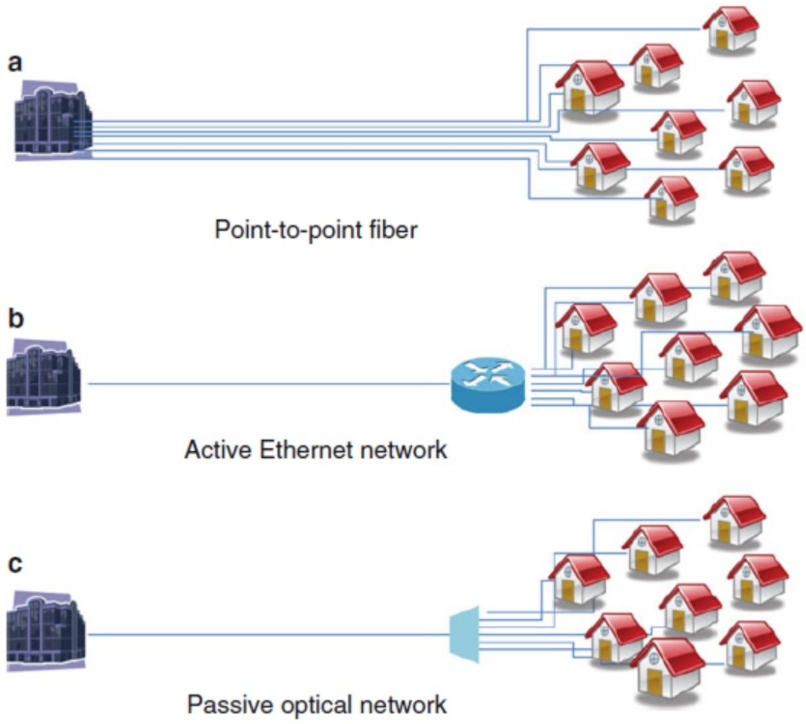


Figure 2.1: Optical Access Network [1]

the network bandwidth, while also meeting the low cost requirements of access networks. Considering the higher capacity that optical fiber offers compared to other broadband access solutions such as Digital Subscriber Line (DSL) and Community Antenna Television (CATV) (cable TV) based networks, an extensive employment of optical fiber in the access network has been seen as an effective solution to accommodate the proliferation of bandwidth demanding broadband applications [1].

Optical access networks offer an all-optical link between the ISP and the end users. We generally distinguish between three main types of optical access networks, as depicted in Fig. 2.1: point-to-point (P2P) fiber, active Ethernet network, and passive optical network (PON). In a P2P fiber network, there is a direct optical connection all the way from the CO to the subscriber's premises. The quantity of fiber in this network architecture is a downside. Active Ethernet network reduces the number of fiber terminations at the CO by deploying electrically-powered equipment, such as switches and routers, installed in secured cabinets between the CO and subscriber's site, to deliver the optical signals. Nonetheless, this necessitates high investment in the outside plant. In contrast, PON, unlike active Ethernet network, does not require active components between the CO and the user premises. It uses a passive optical splitter instead of an Ethernet switch to guide the traffic throughout the network, thereby eliminating the need for powering and maintaining active elements, and for expensive street cabinets [20]. PON has multiple benefits, as it allows for greater distances between the ISP's CO and the customer premises, and provides higher bandwidth, higher flexibility and optical scalability; it also reduces the capital cost and overall life-cycle operational expenditure [21], [22].

2.1.1 Network Architecture

A generic PON system consists of an Optical Line Terminal (OLT) and a number of Optical Network Units (ONUs). The OLT is located at the CO, and connects the access network to the Metropolitan Area Network (MAN) or Wide Area Network (WAN), thus providing the interface between PON and the backbone

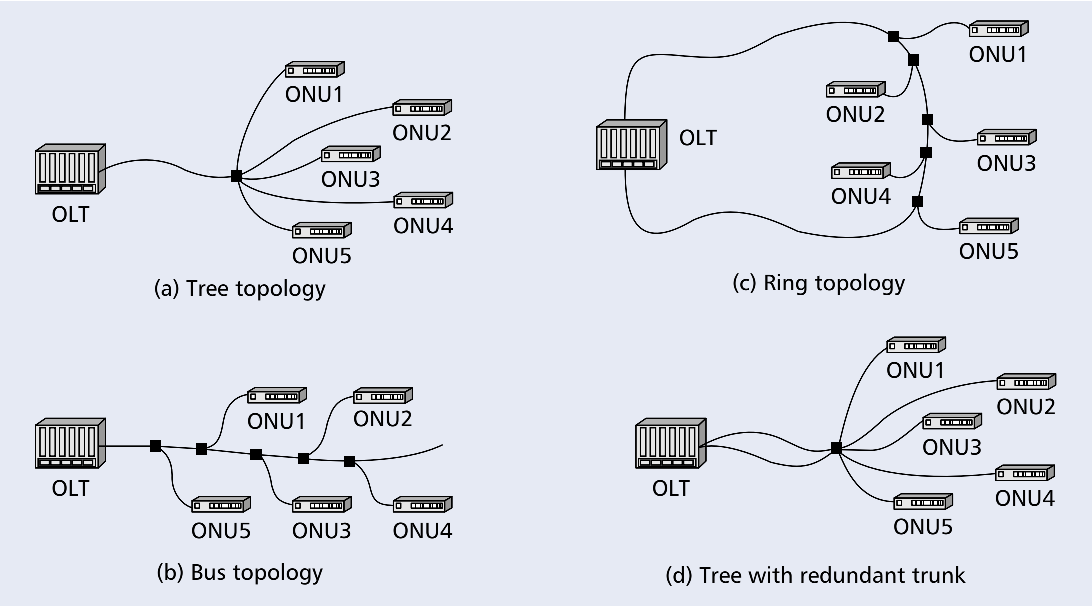


Figure 2.2: PON Topologies [2]

network. The ONU is located near the end-users, thereby providing them with the service interface. The Optical Distribution Network (ODN) in PON connects the OLT and ONUs using optical fibers and splitters. As illustrated in Fig. 2.2, the ODN can form one of several multipoint topologies suitable for the access network, including tree, ring, bus, and tree with redundant trunk.

In the downstream direction (i.e., from the OLT to ONUs), the splitter divides the signal into multiple, identical signals that are broadcasted to the subtending ONUs. Every ONU determines the data intended for it, and discards all others. However, in the upstream direction (i.e., from the ONUs to OLT), when ONUs have to share the upstream channel, collision can't be detected easily if two or more ONUs transmit signals simultaneously. Therefore, a medium access control (MAC) mechanism is required to arbitrate the transmission of ONUs over the shared media.

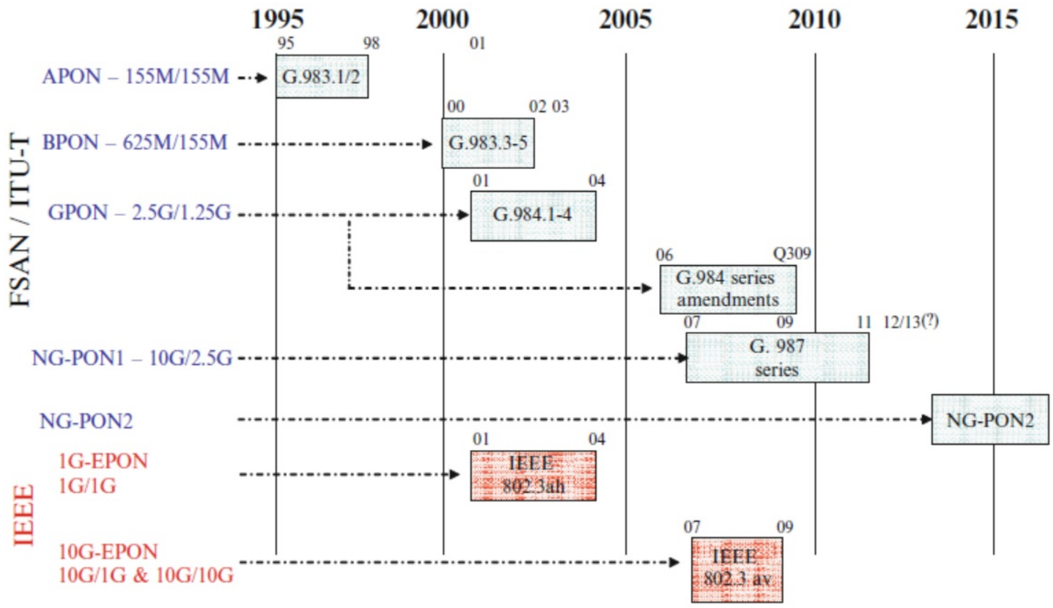


Figure 2.3: Evolution of PON [3]

Fig. 2.3 illustrates the evolution of PON over time. ATM PON (APON), Broadband PON (BPON), Gigabit PON (GPON), and Next-generation PON (NG-PON) were standardized by the Full Service Access Network (FSAN), whereas Ethernet PON (EPON) was standardized by the IEEE 802 study group. APON is the first PON specification defined by FSAN in 1995, which uses Asynchronous Transfer Mode (ATM) as its signalling protocol in Layer 2. Upstream transmission is in the form of bursts of ATM cells. Consequently, in year 2000, BPON emerges as an evolution of APON, which offers numerous broadband services, including ATM, Ethernet access, and video distribution. In year 2002, GPON was introduced with the aim to generalize the support of different data traffic types via GPON encapsulation method (GEM), so as to achieve efficient packaging of user traffic, while enabling frame segmentation. Since then, the ITU-T/FSAN has been working on the standardization of higher bandwidth variants such as NG-PON1 and NG-PON2. However, EPON which is developed based on the Ethernet technology has been the most deployed variant, as it provides seamless integration with IP and Ethernet technologies. Thanks to its fine scalability, simplicity, multicast convenience, and the capability of providing full service access, EPON has been rapidly adopted and became a market leader [3]. Motivated by meeting the emerging high bandwidth demands, the IEEE NG-EPON has been introduced to operate at an aggregate date rate of 10 Gbps per wavelength, and coverage up to 100 Km [12]. Another technology that extends the coverage span of PONs to 100 Km and beyond is long-reach passive optical network (LR-PON), which combines optical access and metro into an integrated system [23].

Optical access architectures can be grouped based on the data multiplexing scheme. The first scheme is orthogonal frequency division multiplexing (OFDM) PON which employs a number of orthogonal subcarriers to transmit traffic from/to ONUs. The second scheme is time-division multiplexing (TDM) PON, where all the ONUs are provided with the same wavelength pair (upstream and downstream). Data to each ONU is multiplexed in time, thereby providing virtual P2P data connections to each ONU over a point-to-multipoint (P2MP) media. The third scheme is wavelength-division multiplexing (WDM) PON, where each ONU gets at least one dedicated pair of wavelength channels, thus creating logical P2P links between the OLT and the ONU. Usually, ONUs are equipped with either wavelength-specified (fixed) lasers that can only transmit over one specific wavelength (thus, are often called "colored" ONUs), or tunable lasers that are able to transmit over multiple wavelengths (thus, referred to as "colorless" ONUs), one wavelength at a time, which facilitates multiplexing the traffic of all ONUs. In a time and wavelength division multiplexing (TWDM) Hybrid-PON, a group of ONUs is equipped with at least one pair of wavelength channels shared in a TDM manner, such that P2MP links are established between the OLT and a specific group of ONUs. Hybrid-PON is further classified based on the method a group of ONUs shares its assigned wavelength channels into multiple scheduling domain (MSD)-WDM-PON, single scheduling domain (SSD)-WDM-PON, and wavelength agile (WA)-PON. In MSD-WDM-PON, each ONU is allowed to transmit on only one upstream wavelength at a time. In SSD-WDM-PON, every ONU transmits on all upstream wavelengths at the same time. As for WA-PON, an OLT grants access to a variable number of wavelengths to a specific ONU, such that every ONU transmits on its allocated upstream wavelengths concurrently with other ONUs.

2.1.2 Multi-Point Control Protocol

The IEEE 802.3ah standard defines a signalling access protocol called multi-point control protocol (MPCP) as the MAC layer control protocol for the management of information transfer in the upstream direction in EPON [24]. MPCP is an in-

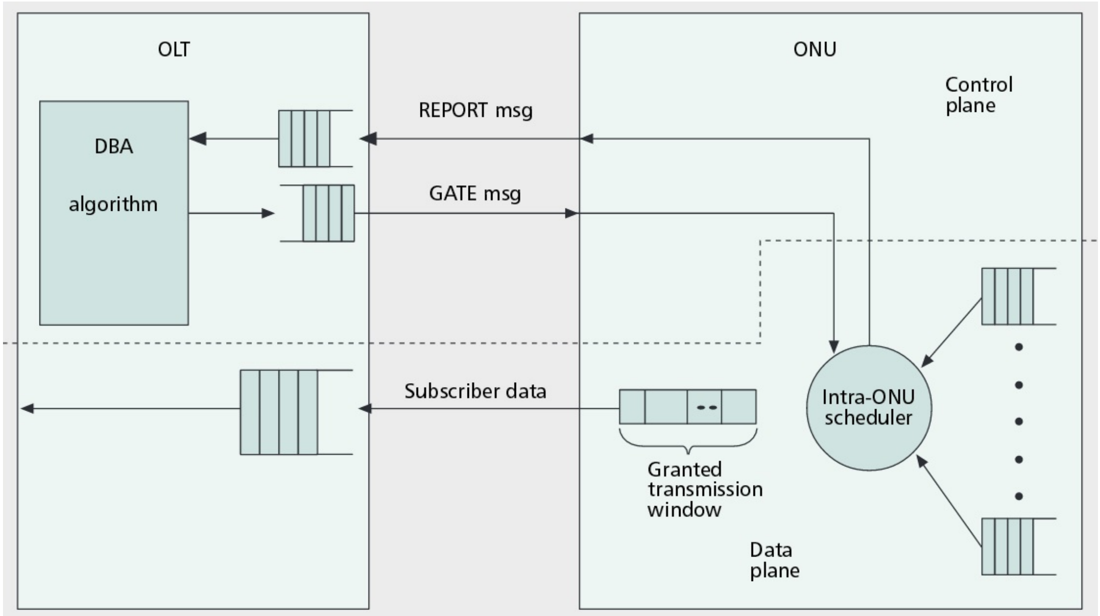


Figure 2.4: MPCP operation: Two-Way Messaging Assignment of Time Slots for Upstream Transmission between ONU and OLT [4]

band signaling protocol that performs many functions including auto-discovery, ONU registration, ranging, bandwidth polling, and bandwidth assignment via a set of 64-byte control messages: REGISTER REQUEST, REGISTER, REGISTER ACK, GATE, and REPORT. The ONU discovery and registration are used to detect newly connected ONUs and register them automatically. MPCP enables a MAC client to perform a P2MP communication by allowing it to transmit and receive frames as if it is connected to a dedicated link. Note that MPCP does not allow packet fragmentation within the same transmission window. If a packet does not fit within the current time slot, it gets differed to the next slot. Fig. 2.4 shows the MPCP operation for the two-way messaging assignment of time slots for upstream transmission between the ONU and OLT. First, the

REPORT message sent by the ONU in the upstream direction is used to report the bandwidth requirements, i.e., the buffers occupancies. The status of up to eight queues, that are used for prioritization of traffic or for providing differentiated services, can be indicated. Upon receiving the REPORT messages from all ONUs, the OLT computes the non-overlapping transmission windows granted for the next cycle via a bandwidth allocation algorithm, and sends the decision using GATE messages in the downstream direction. Up to four transmission grants can be supported by a GATE message. However, the MPCP protocol does not define any particular bandwidth assignment algorithm [25]. The implementation is left to the operator.

2.1.3 Dynamic Bandwidth Allocation

The arbitration of ONUs traffic over the shared media consists of grant sizing, grant (inter-ONU) scheduling, and queue (intra-ONU) scheduling, as shown in Fig. 2.5. Grant sizing specifies the length of the transmission window allocated to an ONU for a given grant cycle. Grant scheduling arbitrates the ONU grants ordering for a given cycle. Intra-ONU scheduling determines the scheduling of the queues at the same ONU for transmission within the granted transmission window.

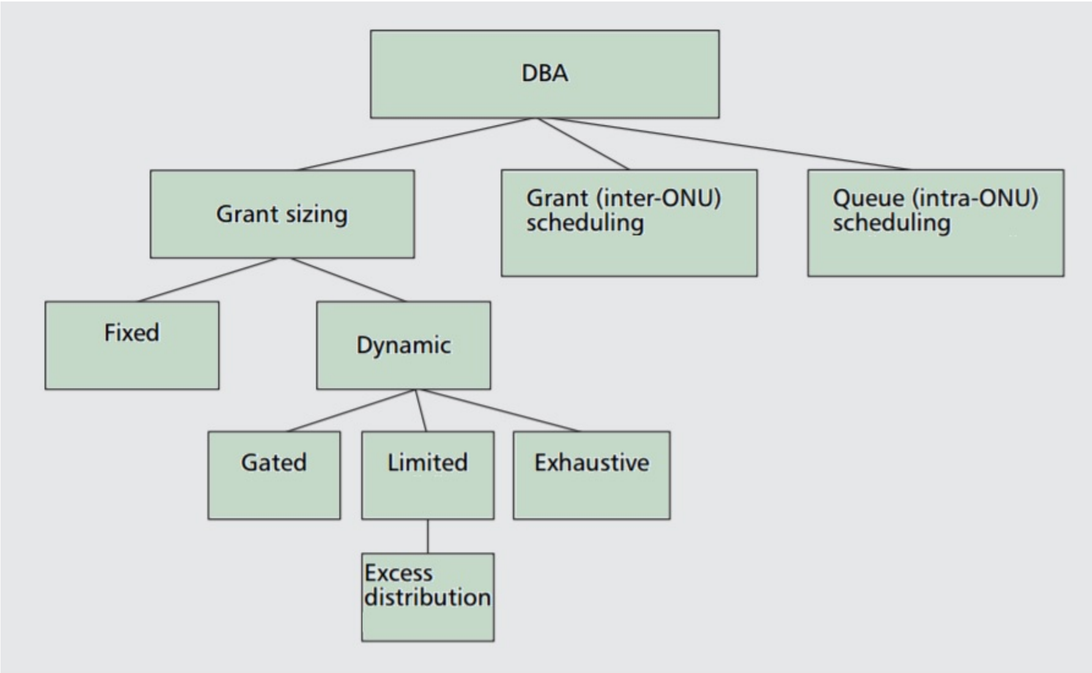


Figure 2.5: Dynamic Bandwidth Allocation Taxonomy [4]

2.1.3.1 Grant Sizing

Multiple grant sizing algorithms have been introduced in the art. In the fixed grant-sizing scheme, the grant size is fixed for an ONU in every cycle, which severely underperforms the dynamic grant-sizing methods. In the Gated method, the grant size for an ONU is equal to its reported queue size, which provides low average delay but without ensuring fair access between ONUs [4]. In the Limited method, the grant size of an ONU is set to the reported queue size up to a maximum grant size for that ONU, and thus preventing an ONU from monopolizing the network resources [4]. The Limited with Excess Distribution method augments the limited grant-sizing scheme by exploiting the "excess" unallocated bandwidth. ONUs are divided into two groups: underloaded ONUs and overloaded ONUs whose reported queue size is less and greater than the maximum grant size, respectively. The total excess bandwidth is the sum of the differences between the maximum grant size and the reported queue size of all underloaded ONUs. The overloaded ONUs share the total excess bandwidth left over from underloaded ONUs. The excess bandwidth can be distributed based on multiple schemes, such as the Round-Robin (RR) scheme or a fair-excess (FE) allocation scheme that assigns portions according to the ONU's bandwidth demand [26]. Another grant-sizing scheme is the exhaustive method, which can lower the packet queuing delays by using queue size prediction disciplines to estimate the traffic generated during the period between the REPORT message transmission and the beginning of the transmission window. However, imprecise predictions may lead to a reduced throughput, due to the wasted portions of a grant, especially if the data traffic is of a bursty nature [4].

2.1.3.2 Inter-ONU Scheduling

As an EPON Dynamic Bandwidth Allocation (DBA) algorithm, interleaved polling with adaptive cycle time (IPACT) provides an improvement to EPON performance [27]. In IPACT, the OLT serves every ONU only once per RR polling cycle. Here, the OLT records the round-trip time (RTT) of each ONU to send a grant to the next ONU so that the un-utilized waiting time between consecutive upstream transmissions is decreased. Owing to the fact that the grants are scheduled with regard to the corresponding RTTs and granted window sizes, the order of the grants may be different in every cycle, and the cycle time is not static.

Longest queue first (LQF) and earliest packet first (EPF) have been examined for ONU transmission ordering [28]. In LQF, ONUs having the largest grant size transmit first. In EPF, ONUs with the earliest arriving head-of-line (HOL) packet transmit first. Both methods provide lower average delay at medium loads compared to a RR scheduler.

A multiple-upstream-wavelength version of IPACT for WDM-PON, referred to as WDM IPACT-ST, is proposed in [29]. It keeps track of the available time on every upstream wavelength. When the OLT receives a REPORT from an ONU, it schedules the ONU's next transmission grant on the next available wavelength, assuming that each ONU supports all wavelengths, which is known as the earliest-channel-available-first rule. Since for cost purposes an ONU may not support all available wavelengths, the authors in [30] proposed to select the next available supported wavelength for scheduling, which is known as the next-available-supported-channel-first.

Online, offline, and just-in-time (JIT) scheduling are three scheduling frameworks introduced in [31] that are used to determine when and how the OLT performs DBA. In online scheduling, the OLT allocates bandwidth to an ONU directly after receiving this ONU's REPORT. Even though this allows the ONU to receive immediate grants, it may lead to unfairness for other upcoming ONU's requests. To achieve better fairness, the offline scheduling determines the bandwidth allocated after receiving all ONU's REPORTs. Nonetheless, this method may lead to increased delays to receive grants. To overcome the two shortcomings of online and offline methods, the JIT operation defers the allocation decision until one channel is about to become idle.

A water-filling algorithm for WA-PON was introduced in [32]. The depression storage is the wavelength resource and the water is the time window requested by an ONU. The finish time of the last reservation on each wavelength is the storage bed of every stage. Reducing the water surface while filling the required time window is the main goal. This results in finishing the transmission of every request as soon as possible, thereby minimizing the packet delay. This is done by iteratively reserving new wavelengths and allocating more bandwidth until the allocated bandwidth equals the requested bandwidth. In case all the supported wavelengths are reserved, and the aggregate time slot has not been yet met, the remaining required time gets equally distributed over the supported wavelengths. When the start time of the previous wavelength(s) is smaller than the current one being allocated, a minimum is distributed between the remaining required time and the difference between the surfaces of the wavelengths, so as not to allocate additional un-granted time slots. For a more comprehensive survey on DBAs in PON, we refer the reader to [4] and [33].

2.1.3.3 Intra-ONU Scheduling

Upon receiving traffic flows from the connected users, the ONU classifies the arriving packets by the means of a packet-based classifier, and decides if a packet should be admitted depending on the used traffic policing (admission control) mechanism. It then selects packets from its queues, depending on the intra-/inter-ONU scheduling algorithm. Typically, two types of scheduling schemes that serve multiple queues of differing priority exist: Strict Priority (SP) and QoS-aware scheduling algorithms. SPs can be unfair as they might lead to starving lower priority traffic. Non-strict priority scheduling algorithms tackle this problem by allowing all traffic classes to have access to the upstream channel while respecting their priorities [34].

To compensate for the light-load penalty, Kramer et al. [35] proposed a two-stage queuing system, where incoming packets, before sending REPORT, are queued in the first-stage, and those arriving after sending the REPORT message are queued in the second-stage. High priority traffic in the second-stage queue are not allowed to preempt the transmission of the low priority traffic. However, this leads to an increased average delay for all traffic types.

An intra-ONU frame scheduler that employs a modified start-time fair queuing (M-SFQ) algorithm was proposed in [36]. The start time of the HOL packet in each queue is computed, and the queue with the minimal start time is selected for transmission. A major setback of this method is that it tends to starve low priority packets.

An effective intra-ONU scheduling method, so-called Modified Deficit Weighted Round Robin (M-DWRR), which addresses the previous shortcomings, is introduced in [37]. In a typical Deficit Weighted Round Robin (DWRR), a weight

α_{i} that defines the percentage of the output port bandwidth allocated to the queue i, a Deficit Counter DC(i) that specifies the total number of bytes that the queue is permitted to transmit in each schedulers visit, and a quantum $Q(i)$ that is proportional to α_{i} and is expressed in bytes, are used for performing intra-ONU scheduling. First, a RR scheduler sets DC(i) to zero for all queues. Then, it passes over every non-empty queue and determines the size (in bytes) of the HOL packet. The quantum Q(i) is computed as: $Q(i) = \lceil \alpha_{\text{i}} \times B_{port} \rceil$, where B_{port} is the bandwidth available on the transmission port (in bytes). Consequently, M-DWRR adds to $DC(i)$ the value of $Q(i)$. At this point, the scheduler checks if the HOL packet is greater than $DC(i)$; if that's the case, it moves to the next queue and saves the remaining credits in $DC(i)$, otherwise it selects the packet for transmission and updates $DC(i)$ as follows: $DC(i) = DC(i) - S_i^{HOL}$, where S_i^{HOL} is the size of the HOL packet in queue i. $DC(i)$ is reset to zero when the queue is empty, and the pointer of the RR scheduler shifts to the lower priority queue. In the case of M-DWRR, whenever the scheduler has finished passing over all the queues, the remaining bandwidth of ONU j is distributed to all the queues such that $DC(i, j) = DC(i, j) + \alpha_{\text{i, j}} \times \lceil B^j_{remain} \rceil$, where B^j_{remain} is the remaining bandwidth (in bytes) from the assigned transmission window of the same cycle. For a comprehensive survey on intra-ONU scheduling in PON, we refer the reader to [4] and [33].

2.1.4 Quality of Service Support

QoS control plays an important role in providing better service to particular network traffic over different technologies, specifically when the requirements of queues have to be sacrificed at high traffic load. Considering various QoS requirements of applications, including dedicated bandwidth, controlled jitter and latency, and loss characteristics, many strategies have been proposed to distribute the bandwidth among queues of the ONU. Differentiated Services (DiffServ) framework was incorporated into IPACT in [35] and [38]. DiffServ classifies the incoming traffic into three classes: expedited forwarding (EF), which corresponds to delay sensitive applications, assured forwarding (AF), which corresponds to bandwidth demanding services, and best effort (BE), which corresponds to applications with no specifications.

In [39], the authors presented a QoS-DBA in TDM/WDM EPONs where they perform protection for EF traffic by dedicating a wavelength for the EF packets. As this technique results in wasted bandwidth and underutilized channel since EF traffic has a low load, they then suggest allowing traffic of lower priorities to use the wavelength dedicated to EF traffic up to a certain limit without impairing the QoS requirements of the supported Classes of Services (CoS).

In [19], the authors classify the ONU traffic as Tactile and Non-tactile in TWDM PON. Using the Bayesian and maximum-likelihood sequence estimation (MLSE) for poisson and paretto traffic distributions, respectively, the OLT predicts the total requested bandwidth and averages it (BW_{avg}) over the ONUs. The OLT computes the maximum allowable bandwidth per ONU (BW_{max}) based on the required end-to-end delay constraint, assuming first that only one wavelength is used. The OLT keeps on dynamically varying the number of active wavelengths in the network to maintain $BW_{max} > BW_{avg}$. However, the estimation scheme assumes knowledge of the traffic distribution, which is impractical. In addition, the scheme does not report the network performance in terms of networks throughput.

2.2 Cloud Computing

Owing to the fact that high bandwidth with relatively lower operating expenses is provided by PON, delivering cloud services over PON is an attractive solution to meet the stringent requirements of future cloud services [8]. Cloud computing is an important paradigm that revolutionized computing by providing a new way to store, access, and exchange information. It enables the usage of computing resources on third-party facilities instead of local equipment, thereby allowing private or public networks to connect a large pool of systems to provide dynamically scalable infrastructure. Cloud computing has gained popularity thanks to the technical and economical benefits of the on-demand capacity management model [40]. It is especially attractive to business owners and enterprises for its compelling features such as the pay-as-you-grow pricing model that doesn't require up-front investment, and lower operating cost due to the fact that resources are managed based on demand; in addition to expanding services easily thanks to the highly scalable infrastructure, which allows easy access to services through a variety of devices, meanwhile reducing business risks and maintenance expenses [5].

Many cloud operators are now active on the market, providing rich services such as Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS) solutions. Fig. 2.6 illustrates a typical cloud

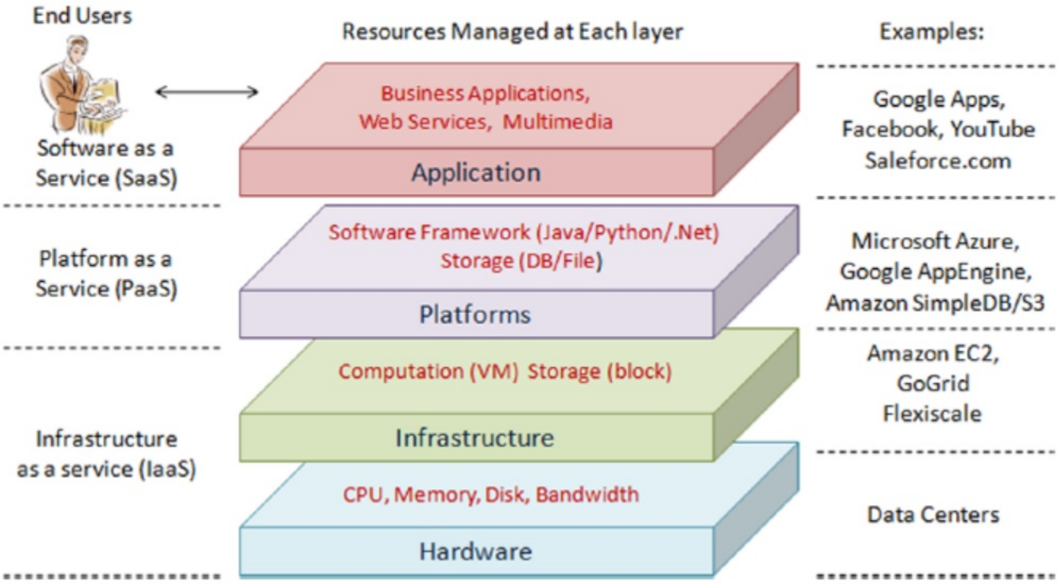


Figure 2.6: Cloud Computing Architecture [5]

computing environment. IaaS refers to the on-demand provisioning of services like storage, database management, and compute capabilities. Infrastructural resources are pooled and made available to handle workloads [5]. Some common examples are Amazon EC2 [41] and GoGrid [42]. In PaaS, a platform layer, including operating system support and software development frameworks, is encapsulated and provided as a service, upon which other higher levels of service can be built [5]. Google's App Engine [43] and Salesforce.com [44] are some of the popular PaaS examples. In SaaS, a complete highly scalable application is offered to the customer over the Internet, as a service-on-demand [5]. Today, SaaS is offered by companies such as Salesforce.com [44] and Rackspace [45].

Architectures that make use of PON to offer cloud services have been introduced in the art [13], [14]. These architectures suggest provisioning PONs nodes (i.e., OLT and ONUs) as a network of distributed cloud servers acting as a single large-scale server. Unfortunately, this would impose additional delays that cannot be tolerated by delay-sensitive application such as Tactile Internet.

2.3 Tactile Internet

The notion of the Tactile Internet is expected to reshape our society with its great potential impact, as it allows the transmission of touch and actuation in real-time. Multiple new application fields will play a major role in finding solutions for todays' challenges. A new dimension to M2H interaction is introduced through building real-time interactive systems. Emerging Tactile Internet applications are advancing towards precise human-to-machine, as well as a well-recognized trend, M2M interaction [46]. Education, healthcare, mobile access, and smart grid are some of the many other application areas that will be revolutionized by Tactile Internet. Interactive methods far more advanced than today's will be introduced to modern techniques for teaching, via introducing a haptic experience between the teacher and the learner. The performance of remote diagnosis and treatment, as well as robot-assisted operations, will be supported to provide better healthcare quality. The mobile access field will experience an improvement in the aspects of safety and energy-efficiency by exploiting applications for vehicle safety and guided autonomous driving that allow for continuous traffic flow. Smart grids, which are technically constructed over Tactile Internet, will provide an efficient and reliable energy transmission and distribution in electricity networks. The strict latency requirements caused by the technical boundary conditions of smart grids to cascade power networks failure will be met by Tactile Internet [46].

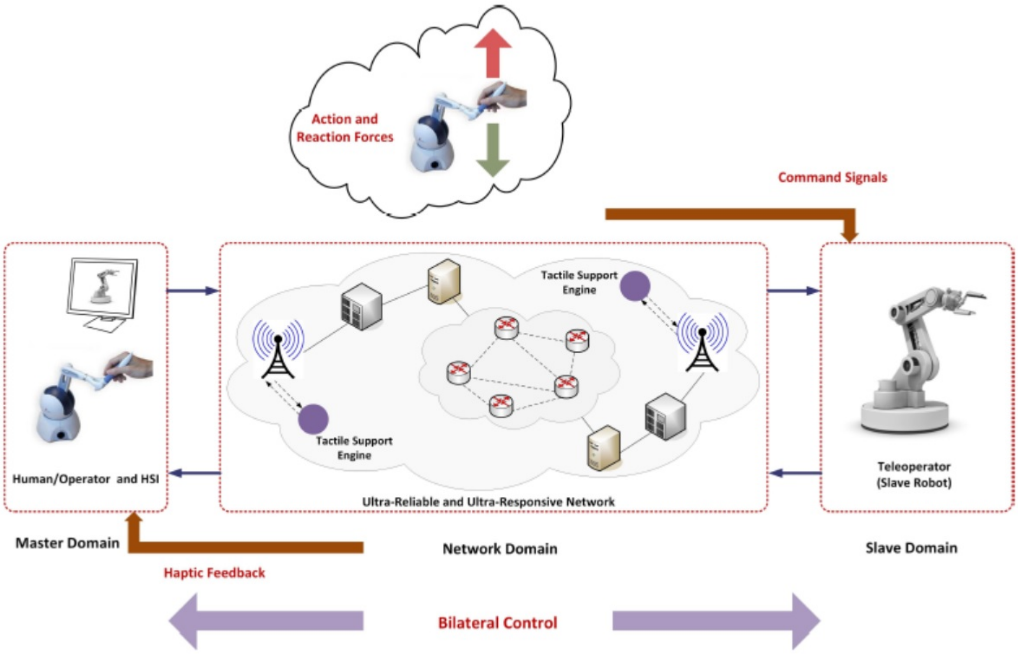


Figure 2.7: Functional Architecture of the Tactile Internet Providing the Medium for Haptic Transport [6]

More attractively, Tactile Internet will provide the ability of haptic and non-haptic control through the Internet. The haptic sense is similar to the auditory and visual senses as they all link humans with unknown environments. However, what distinguishes the haptic sense is that it occurs bilaterally and is considered multidimensional as it comprises kinesthetic and Tactile inputs, resulting in a true immersion in remote environments [47]. As such, there exists a feedback from the haptic control system, thus closing the global control loop.

As shown in Fig. 2.7, Tactile Internet can be split into three different domains: the master domain consisting of a human operator and a haptic device (master robot) acting as a human-machine interface (HSI), the slave/controlled domain consisting of a slave/controlled robot that interacts with the objects in the remote

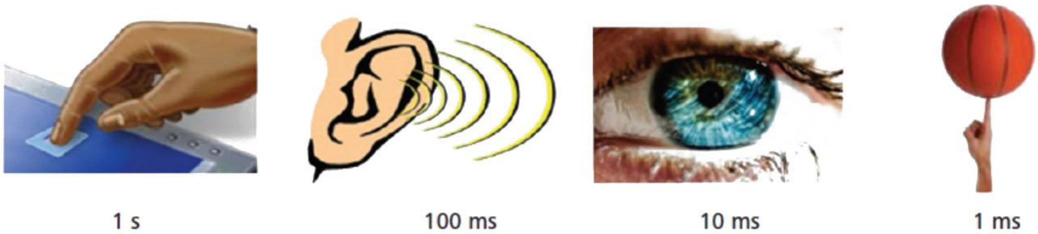


Figure 2.8: Coarse Categories of Physiological Real-time Constants [7]

environment based on command signals sent by the controlling master domain, and the network domain that supports the bilateral communication between the master and slave/controlled domains to kinaesthetically link the human to the remote environment [6], [48].

Achieving real-time haptic communication necessitates specific design requirements. These design requirements are reliability, security, ultra-low latency, and high availability [6], [18] . Reliability refers here to the probability to guarantee a required function/performance under stated conditions for a specified time interval [49]. Security means that if an illegitimate person receives data, then she will not be able to decode it, even with infinite computational power [48]. Tactile Internet applications require a very stringent round-trip latency of 1 ms, enabling it to deliver physical haptic experiences remotely. This delay is initially set within the context of human tolerance, which varies for different senses, as shown in Fig. 2.8. Tactile's very low end-to-end latency needs to be supported to avoid the users' experience of "cyber-sickness" [17], which is the digital version of motion sickness (observed with people using flight simulators over poor networks). This end-to-end delay is composed of a chain between sensors and actuators.

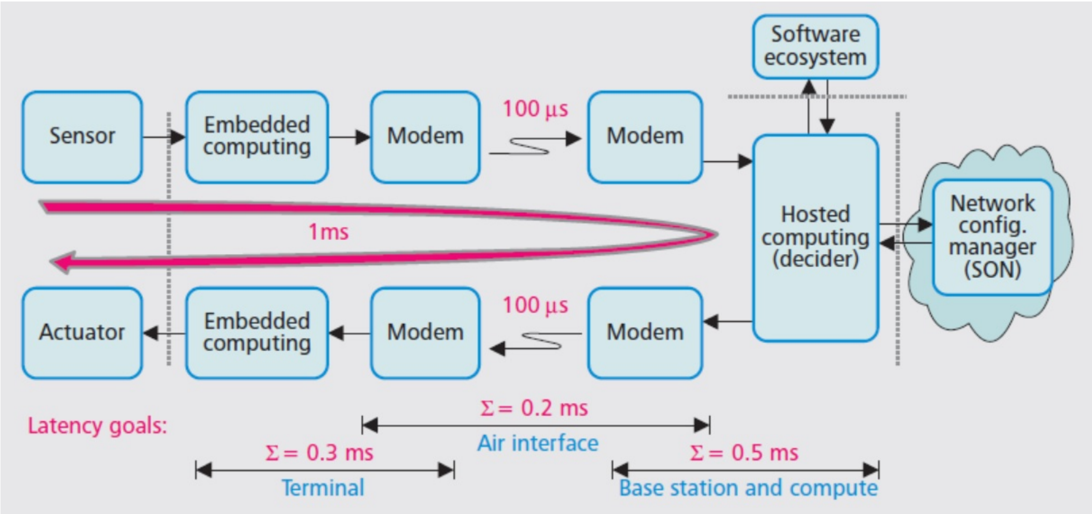


Figure 2.9: The Impact of Breaking Down the 1 ms Round-Trip Delay [7]

Understanding this chain is fundamental to achieve a round-trip latency of 1 ms, and thus a system response of 1 ms. The end-to-end delay of Tactile packets can be divided into three sub-chains composing of the user interface (300 µs), radio interface (200 µs), and Base Station and Control/Steering server (500 µs). Fig. 2.9 shows one example of the latency budget for the Tactile Internet. It considers the latencies from "the sensor through the operating system, the wireless/cellular protocol stack, the physical layer of terminal and base station, the base stations protocol stack, the trunk line to the compute server, the operating system of the server, the network within the server to the processor, the computation, and back through the equivalent chain to the actuator" [7]. With stringent latency constraints, Tactile Internet applications require a highly available network. As such, an efficient DBA is required to support Tactile services over PON. The only attempt to do so is presented in [19], which fails to meet the Tactile's traffic delay requirements using a predictive approach when having a Pareto-distributed traffic arrivals. Therefore, efficient DBA design is required to meet the strict QoS demands of tactile services, without impairing the requirements of existing services.

2.4 Content Distribution Network

Deploying ISP-based CDN at the OLT pushes resources closer to the end-users' premises, which has become a necessity to support delay-sensitive services, such as cloud and Tactile applications. A CDN is a network of content delivery nodes, mainly center servers and edge servers distributed in different geographic locations. The nodes are arranged efficiently to deliver digital content on behalf of third-party content providers near the end-users. CDN is an acceleration technology as it aims at a near-optimal path, by guiding a request from an end-user to the replica server, which serves the client quickly compared to the time it would take to fetch it from the origin server (typically residing in the core network) [50]. The CDN technology can solve the network bandwidth bottleneck and response time problem of video business [16].

It has become an appealing trend of ISPs to deploy CDNs largely in their infrastructure to efficiently utilize their network resources and create a new profit source [51]. Multiple ISPs have started providing services to content providers to serve content from caches nearer to users by deploying proprietary CDNs inside their own network [52]. They do so by deploying caches and content streamers within their network and providing the capability to link their CDN to their own network, which is already enabled for QoS [11]. OCLDN exploits the CDN infrastructure to enable ISPs deliver killer cloud and tactile services, so as to generate more revenues.

Chapter 3

OCLDN Architecture

Architectures that make use of PON to offer cloud services have been introduced in the art [13,14]. However, these architectures suggest provisioning PON's nodes (i.e., OLT and ONUs) as a network of distributed cloud servers acting as a single large-scale server. This would impose additional delays that can not be tolerated by delay-sensitive application such as Tactile Internet. Thus, in our proposed architecture, we maintain the centralized architecture, and make use of a state-of-the-art programmable wavelength-agile (WA) NG-EPON technology, coupled with an efficient bandwidth allocationscheme to support delay-sensitive cloud applications.

3.1 Proposed Network Architecture

Fig. 3.1 illustrates the proposed architecture, which employs a time-and-wavelength division multiplexing (TWDM) WA-NG-EPON [12]. The reason behind this selection is to dedicate wavelength(s) for tactile traffic (so as to meet their strict

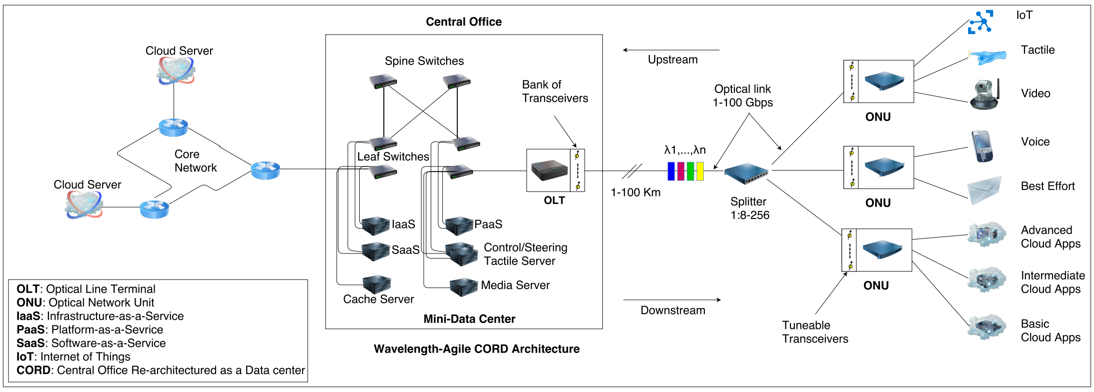


Figure 3.1: Proposed OCLDN Architecture.

delay requirements), and enable the implementation of bandwidth allocation schemes that allow for inter-channel statistical multiplexing so as to increase the network throughput, and reduce the potentially wasted bandwidth caused by having different cycles over different wavelengths, which may impede the stringent QoS requirements. As per the standard, a typical NG-EPON technology supports an aggregate data rate of $40Gbps$ by multiplexing up to four 10 Gbps wavelength channels with coverage up to $100Km$ [12]. Every ONU can be equipped with fixed or tunable transceivers. In the latter case, an ONU equipped with two tunable lasers would be capable of transmitting over all upstream wavelengths, which is the optimal number of lasers for a PON with four wavelengths as shown in [32]. However, the architecture can scale in a "pay-as-you-grow" manner, such that more wavelengths and transceivers can be added as needed.

To meet the supported application services' requirements, a mini-data center comprising cache, media and cloud servers, is installed at the CO nearby the users [53]. In addition, a control/steering server is installed in the mini-data center to support cloud-based tactile applications. Similar to cloudlets and mobile edge computing, the server will perform predictive real-time execution of tactile applications such as caching and resource allocation, which will be possible due to the small distance between the steering server and the tactile edge [19]. The internal architecture of the central office is based on the state-of-the-art CORD architecture (i.e., Central Office Re-Architected as a Data Center) [54]. The main advantage of CORD is employing software running on commodity servers, white-box switches, and access devices instead of closed and proprietary hardware. The interconnection between the OLT and the servers is established via a leaf-spine switching fabric. The components are grouped into two virtual racks; two spine switches are connected to two leaf switches per virtual rack, a leaf switch is connected to an Internet router, and the OLT is connected to the ONUs. Although similar in design (albeit on a smaller scale) to a conventional data center, a distinctive aspect to this hardware configuration is that the switching fabric is optimized for traffic flowing between the access network that connects customers to the CO and the upstream links that connects the CO to the operator's backbone.

CORD is based on the software-defined networking (SDN) technology that separates the network's control plane from its data plane, thereby making it flexible, programmable, and scalable [55]. It also combines SDN with the network functions virtualization (NFV) technology that decouples the data plane from proprietary hardware appliances, so as to run on virtual machines running on commodity servers. Using CORD, OCLDN would be able to offer or support new network services that are faster and cheaper so as to realize better service agility by providing the necessary tools to design networks with a greater degree of abstraction [56]. OCLDN can be adopted by several ISPs that plan to deploy an SDN-NFV network infrastructure (e.g., Verizon and AT&T have already devised plans for year 2020 to virtualize and control over 75% of their networks using SDN/NFV [57, 58]).

Locating CORD-based mini-data centers at the OLT, would enable ISPs to be engaged in the content delivery of killer cloud services closely to the users, meeting their stringent QoS demands, and adding new sources of revenues. With OCLDN, if a required application can not be served by the CO-based server, the data is fetched from the core servers. The decision of what cloud services are to be employed at the CO versus at the core network, is left to the network operator's preferences, service offerings, and geographical location. The specifics of the interconnection between the ISP's cloud servers and the cloud servers can follow CO-Cloud connection standards [14].

3.2 QoS Support

As illustrated in Fig. 3.2, in addition to the legacy data services, OCLDN can deliver four classes of cloud-based services [8]: 1) *Basic*, such as collaborative web conferencing, and cloud-based learning management systems; 2) *Intermediate*, such as augmented reality gaming applications, and web-based electronic health records; 3) *Advanced*, such as mission-critical applications e.g., connected vehicles safety applications, and telemedicine; 4) *Tactile*, such as robotic surgery and robotic artist.

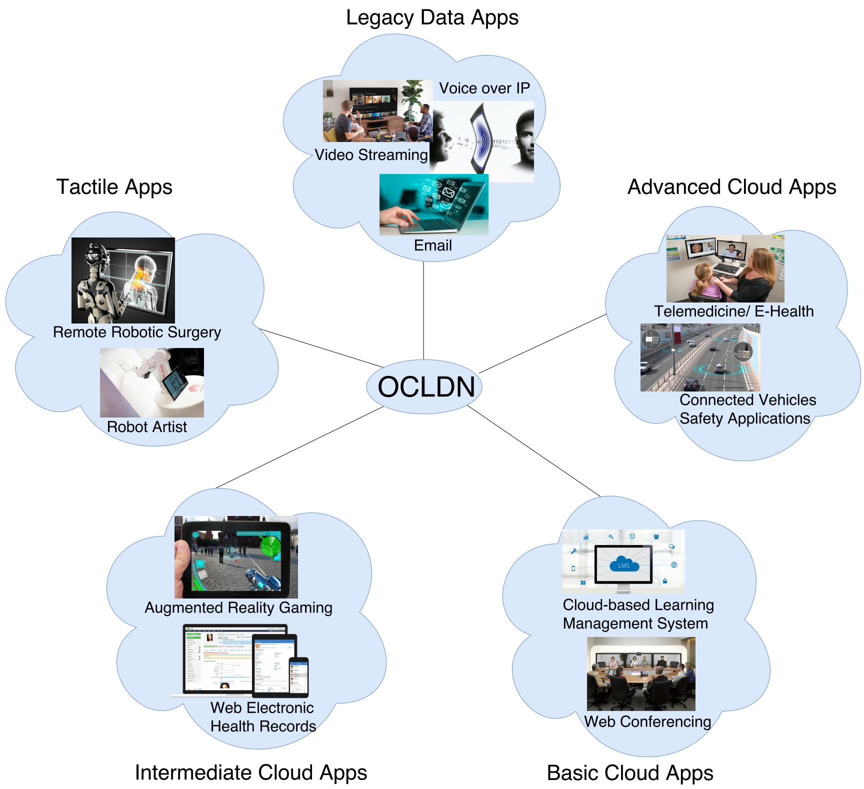


Figure 3.2: Illustration of enabled applications using OCLDN.

To support the different cloud services over OCLDN, we perform traffic classification at the ONU based on the traffic type, characteristics, and QoS requirements. Table 3.1 lists the different service categories and their corresponding network requirements, and their CoS mapping at the ONU. The values presented in the table are deduced based on reports in [8, 46, 59, 60]. Intermediate cloud services and legacy video data services are mapped to the same CoS since they

Table 3.1: QoS Requirements and CoS Mapping in OCLDN.

	Service Type	Example Applications	QoS Requirements		CoS Priority
			Data Bit Rate	One-way End-to-end Delay	
Cloud Services	Tactile	Telesurgery	10 – 100 Mb/s	$\leq$ 0.5 ms (Up. data + Down. steering/control)	1
		Virtual Reality			
	Advanced	Ultra HD Video Streaming	25 – 600 Mb/s	<100 ms (User-to-cloud)	2
		High-frequency Stock Trading			
	Intermediate	Voice over LTE	25 – 34 Mb/s	100 – 159 (User-to-cloud)	4
		HD Video Streaming			
	Basic	Music Streaming	1 – 5 Mb/s	$\geq$160 ms (User-to-cloud)	5
		Cloud-based Learning Management System			
Legacy Data Services	Voice	Voice over IP	4 – 128 Kb/s	100 – 150 ms (Access delay)	3
		Audio Conferencing			
	Video	Video Streaming	20 Kb/s – 6 Mb/s	150 – 250 ms (Access delay)	4
		Video Conferencing			
	Best Effort	Email	Minimum throughput		6
		Web Browsing			

share similar QoS requirements. As noticed, each ONU would subsequently be equipped with six CoS queues.

The breakdown of the end-to-end round-trip delay of cloud-based tactile services in OCLDN, with an example of "cloud-controlled" machine-to-human communication is illustrated in Fig. 3.3. This delay can be divided into three budgets: two-way user interface delay of 0.3 ms, two-way network interface delay of 0.2 ms, and two-way access delay of 0.5 ms (consisting of upstream data + downstream steering control) [48]. The same logic applies for machine-to-cloud, where the actuator and sensor are for the same machine.

3.3 Enabled Services

In addition to the legacy data services, our architecture supports four categories of cloud services: *Basic*, *Intermediate*, *Advanced*, and *Tactile*. Figure 3.2 shows examples of applications of each of the cloud categories which are described, as

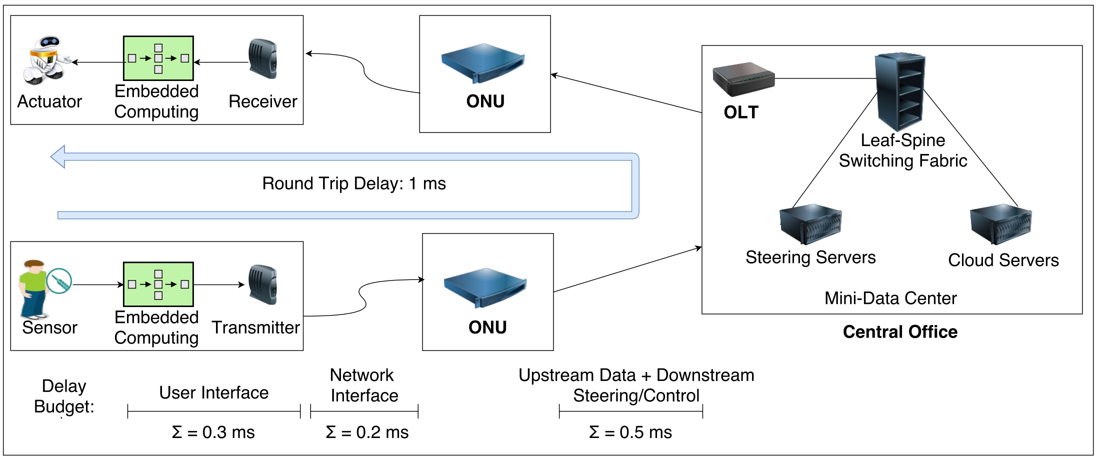


Figure 3.3: Breakdown of the 1 ms end-to-end delay of tactile packets in OCLDN.

follows [8], [46], [61], [62]:

1. Legacy Data Applications

   - **Voice over IP**: Allows users to transmit voice over the Internet through a broad range of services.
   - **Video Streaming**: Delivers video via the Internet such that a remote web user can view the video online without the need to download it on the host device.
   - **Email**: Exchange of messages electronically via an Internet data plan.

2. Basic Cloud Applications

   - **Web Conferencing**: Allows interaction with other participants and have a real-time communication with the attendees by offering online services such as collaborative web browsing and application sharing.

- **Cloud-Based Learning Management System**: Delivers online courses to users with the flexibility of accessing and collaborating with other users in a centralized environment. With information stored in the cloud, it allows the work to be completed anywhere and on virtually any electronic device.

3. Intermediate Cloud Applications

- **Augmented Reality (AR) Gaming**: Involves a live direct or indirect view of an existing reality integrated with some extra computer-generated sensory input such as sound, video, graphics, or GPS data; thereby creating a composite view that augments the real world.
- **Web Electronic Health Records (EHRs)**: Contains and shares patients medical data from eligible providers, such as nurses and physicians, in a structured format that makes it easy to retrieve and transfer valuable and pertinent information to aid in patient care.

4. Advanced Cloud Applications

- **Connected Vehicles Safety Applications**: Increases situation awareness and mitigate traffic accidents through the development and deployment of a fully connected transportation system based on well-defined technologies, interfaces, and processes. Extra-vehicular data sharing helps ensure safety, stability, and reduction in operation costs.

- **Telemedicine**: Improves the patient's clinical health by permitting two-way real-time communication between healthcare professionals and the patient at a distance using the telecommunications technology, such as two-way video, email, smart phones, and wireless tools.

5. Tactile Applications

- **Remote Surgery**: Allows performing a surgery on a patient remotely via a tele-robot at the patient's location, which requires high-fidelity for safe deployment.
- **Robotic Artist**: Produces a precise replica of the human's work remotely and synchronously by precisely mapping the tracks drawn by a human on a tablet onto a canvas.

Chapter 4

Resource Management in OCLDN

4.1 Mathematical Formulation

Bandwidth allocation schemes aiming to support QoS in PON have been widely investigated in the literature. However, to the best of our knowledge, no prior work has aimed to support cloud services in PON. Similarly, only one recent study in [19] proposed a bandwidth allocation scheme to support tactile services (yet non-cloud based) in TWDM-PON, using the Bayesian and MLSE. However, the estimation scheme assumes knowledge of the traffic distribution, which is impractical. In addition, the scheme only supports one type of non-tactile traffic, and does not report the network performance in terms of network throughput. In contrast, our scheme is designed to be adaptive and works independent of the traffic distribution. It also supports all types of cloud and legacy services, and aims at maximizing the network throughput without impairing the QoS demands for all types of services.

Table 4.1: Most Relevant Notations.

Notation	**Description**
N	Set of ONUs $\{1, \ldots, i, \ldots, j, \ldots, \lvert N\rvert\}$
P	Set of priority queues $\{1, \ldots, p, \ldots, q, \ldots, \lvert P\rvert\}$
M	Set of wavelengths $\{\lambda_1, \ldots, \lambda_k, \ldots, \lambda_h, \ldots, \lambda_{\lvert M\rvert}\}$
Λ_i	Set of wavelengths supported by ONU i, $\Lambda_i \subseteq M$
d	Distance between ONU and OLT
B_i^{min}	Minimum guaranteed bandwidth for ONU i
$R_{i,p}$	Requested bandwidth for priority p traffic of ONU i
t^{str}	Transmission start time for every cycle (on all wavelengths in M)
D_p^{max}	Maximum delay requirement for priority p packets
$t_{i,p,k}$	Instant start time for priority p traffic of ONU i, on λ_k
$L_{i,p,k}$	Transmission length for priority p traffic of ONU i, on λ_k
$E_{i,p}$	Transmission end of ONU i's request for priority p on all wavelengths
$Q_{i,p}$	Queuing delay of traffic priority p at ONU i
T_c	Default polling cycle time
T_c^n	Time of polling cycle n
$\mathcal{C}$	Upstream transmission capacity

In this section, we mathematically formulate the scheduling and grant sizing problem in OCLDN as an MILP optimization problem, for the scenarios where the ONUs can be either equipped with fixed transceivers, or tunable transceivers. Since MILP is NP-complete and does not scale well [63], we propose a novel dynamic wavelength and bandwidth allocation scheme to address the limitations of MILP. The proposed DWBA is further enhanced to increase the network throughput via enabling inter-channel statistical multiplexing without impairing the QoS for all types of services.

For the reader's convenience, the most relevant notations used in this section are summarized in Table 4.1; the rest are defined in the text as they appear.

4.1.1 Fixed Transceivers

When the ONU is equipped with fixed transceivers, the problem is formulated as follows:

Input Parameters:

N, P, M, Λ_i, B_i^{min}, $R_{i,p}$, D_p^{max}, T_c^{n-1}, $\mathcal{C}$

ϱ_p: weight of priority p traffic

$t_{i,p}^{init}$: initial instant start time for ONU i's priority p traffic

$C_{i,p}$: number of polling cycles elapsed until priority p queue of ONU i is full

Θ: a very large positive number

f: minimum packet size

$S_{i,p}$: queue size for priority p traffic of ONU i

$$\delta_{i,k} = \begin{cases} 1 & \text{if ONU } i \text{ supports wavelength } \lambda_k \\ 0 & \text{otherwise} \end{cases}$$

$$\psi_{i,p} = \begin{cases} 1 & \text{if } R_{i,p} \leq \varrho_p \times B_i^{min} \\ 0 & \text{otherwise} \end{cases}$$

Output Variables:

$t_{i,p,k}$, $L_{i,p,k}$, $E_{i,p}$

Binary Variables:

$$x_{ij,pq,k} = \begin{cases} 1 & \text{if } t_{i,p,k} < t_{j,q,k} \quad i \neq j \quad or \quad (i = j, p \neq q) \\ 0 & \text{otherwise} \end{cases}$$

$$y_{i,p,k} = \begin{cases} 1 & \text{if ONU } i \text{ sends priority } p \text{ traffic on } \lambda_k \\ 0 & \text{otherwise} \end{cases}$$

$$\varpi_{i,p,kh} = \begin{cases} 1 & \text{if } t_{i,p,k} \leq t_{i,p,h}, \quad y_{i,p,k} = 1, \quad k \neq h \\ 0 & \text{otherwise} \end{cases}$$

The objective is to minimize the maximum completion time across all channels, i.e., the makespan E^{max}:

$$\min \left(E^{max} \right)$$

subject to:

$$E_{i,p} - t_{i,p,k} \geq L_{i,p,k} \quad \forall i,k,p \tag{4.1}$$

$$E^{max} \geq E_{i,p} \quad \forall i,p \tag{4.2}$$

$$y_{i,p,k} \geq 0 \quad \forall i,k,p \tag{4.3}$$

$$y_{i,p,k} \leq \delta_{i,k} \quad \forall i,k,p \tag{4.4}$$

$$\sum_{k=1}^{|M|} y_{i,p,k} \leq |\Lambda_i| \quad \forall i,p \tag{4.5}$$

$$L_{i,p,k} \leq \Theta \times y_{i,p,k} \quad \forall i,k,p \tag{4.6}$$

$$L_{i,p,k} \geq \frac{f}{\mathcal{C}} \times y_{i,p,k} \quad \forall i,k,p \tag{4.7}$$

$$t_{i,p,k} \leq \Theta \times y_{i,p,k} \quad \forall i,k,p \tag{4.8}$$

$$t_{i,p,k} \geq t^{str} \times y_{i,p,k} \quad \forall i, k, p \tag{4.9}$$

$$x_{ij,pq,k} + x_{ji,qp,k} = 1 \quad \forall i, j, p, q, k \tag{4.10}$$

$$t_{i,p,k} - t_{j,q,k} \leq \Theta \times x_{ji,qp,k} \quad \forall i, j, k, p, q \tag{4.11}$$

$$\begin{aligned} t_{i,p,k} + L_{i,p,k} - t_{j,q,k} \leq \Theta \times (1 - x_{ij,pq,k} + 2 \\ -y_{i,p,k} - y_{j,q,k}) \quad \forall i, j, k, p, q \end{aligned} \tag{4.12}$$

$$\begin{aligned} t_{j,q,k} + L_{j,q,k} - t_{i,p,k} \leq \Theta \times (1 - x_{ji,qp,k} + 2 \\ -y_{i,p,k} - y_{j,q,k}) \quad \forall i, j, k, p, q \end{aligned} \tag{4.13}$$

$$\sum_{k=1}^{|M|} L_{i,p,k} - R_{i,p} \leq \Theta \times (1 - \psi_{i,p}) \quad \forall i, p \tag{4.14}$$

$$-\sum_{k=1}^{|M|} L_{i,p,k} + R_{i,p} \leq -\Theta \times (1 - \psi_{i,p}) \quad \forall i, p \tag{4.15}$$

$$\sum_{k=1}^{|M|} L_{i,p,k} - R_{i,p} \leq \Theta \times \psi_{i,p} \quad \forall i, p \tag{4.16}$$

$$B_i^{min} \times \varrho_p - \sum_{k=1}^{|M|} L_{i,p,k} \leq \Theta \times \psi_{i,p} \quad \forall i, p \tag{4.17}$$

$$t_{i,p,k} - t_{i,p,h} \leq \Theta \times \varpi_{i,p,hk} \quad \forall i, k, h, p \tag{4.18}$$

$$\varpi_{i,p,kh} \leq y_{i,p,k} \quad \forall i, k, h, p \tag{4.19}$$

$$\varpi_{i,p,kh} + \varpi_{i,p,hk} \leq 1 \quad \forall i, k, h, p \tag{4.20}$$

$$t_{i,p}^{init} - t_{i,p,k} \leq \Theta \times (\sum_{h=1}^{|M|} \varpi_{i,p,kh} - \sum_{h=1}^{|M|} y_{i,p,h} - 1) \quad \forall i, k, p \tag{4.21}$$

$$-t_{i,p}^{init} + t_{i,p,k} \leq \Theta \times (\sum_{h=1}^{|M|} \varpi_{i,p,kh} - \sum_{h=1}^{|M|} y_{i,p,h} - 1) \quad \forall i, k, p \tag{4.22}$$

$$\begin{aligned} &\sum_{i=1}^{|N|}((C_{i,p} + 2) \times T_c^{n-1} - (E_{i,p} - t_{i,p}^{init}) - \\ &\sum_{k=1}^{|M|} L_{i,p,k} \times \mathcal{C} \times (\frac{T_c^{n-1}}{R_{i,p}} \times C_{i,p}))/|N| \leq D_p^{max} \\ &\forall p; \sum_{i=1}^{|N|} R_{i,p} > \sum_{i=1}^{|N|} \varrho_p \times B_i^{min} \end{aligned} \tag{4.23}$$

Constraint (4.1) ensures that the transmission end of ONU i's request for priority p is greater than its transmission end on every wavelength. Constraint (4.2) forces E^{max} to be greater than every transmission end $E_{i,p}$. Constraints (4.3) and (4.4) state that $y_{i,p,k}$ will be zero if $\delta_{i,k}$ is zero, that is, ONU i can't send priority p traffic on λ_k if the latter is not supported by the ONU. In case $\delta_{i,k} = 1$, $y_{i,p,k}$ can be either zero or one. Constraint (4.5) ensures that an ONU is only allocated time slots on the wavelengths that it supports. Constraints (4.6) and (4.7) set upper and lower bounds for $L_{i,p,k}$, respectively. More specifically, Constraint (4.6) ensures that if ONU i occupies λ_k with priority traffic p, i.e., $y_{i,p,k} = 1$, then $L_{i,p,k}$ will be upper-bounded by Θ, otherwise it will be set to zero. On the other hand, Constraint (4.7) ensures that if $y_{i,p,k} = 1$, the allocated transmission length would be big enough to allow the transmission of a minimum size packet. Constraints (4.8) and (4.9) set upper and lower bounds for $t_{i,p,k}$, respectively. Constraint (4.9) ensures that the transmission start time for ONU i's request of priority traffic p on λ_k is at least t^{str} if $y_{i,p,k} = 1$. Constraint (4.10) forces the transmission of ONU i's priority p traffic to either precede or follow the transmission of ONU j's priority q traffic, but not both. Clearly, $x_{ii,pp,k} = 0$.

Constraint (4.11) ensures that if $x_{ji,qp,k} = 0$, then the transmission corresponding to priority p of ONU i is scheduled before priority q of ONU j; that is, the scheduled time slots must not overlap. Constraints (4.12) and (4.13) handle this constraint when $y_{i,p,k} = y_{j,q,k} = 1$. When $x_{ij,pq,k} = 1$, then $x_{ji,qp,k} = 0$. As such, Constraint (4.12) evaluates to $t_{i,p,k} + L_{i,p,k} \leq t_{j,q,k}$. This forces the start time of ONU j's request for priority q to be scheduled after the transmission of ONU i's request for priority p is over. Consequently, Constraint (4.13) will evaluate to $t_{j,q,k} + L_{j,q,k} - t_{i,p,k} \leq \Theta$, which is always true.

Constraints (4.14)-(4.17) set the grant size for traffic priority p of ONU i based on whether the requested bandwidth $R_{i,p}$ is smaller than $B_i^{min} \times \varrho_p$, i.e., smaller than the minimum bandwidth for a priority traffic of an ONU. This can be obtained via either setting ϱ_p statically (e.g., based on strict priority policies) or dynamically (e.g., based on buffering queue occupancy), which can enforced using advanced intra-ONU scheduling disciplines [64]. If $\psi_{i,p} = 1$, i.e., $R_{i,p} \leq \varrho_p \times B_i^{min}$, then constraints (4.14) and (4.15) would hold, and the granted bandwidth for priority p traffic of ONU i is equal to the corresponding requested bandwidth. If $\psi_{i,p} = 0$, then constraints (4.16) and (4.17) would hold, and the grant size would be bounded between $B_i^{min} \times \varrho_p$ and the total requested bandwidth $R_{i,p}$.

Constraint (4.23) computes the estimated maximum one-way delay for any priority p traffic (i.e., from ONU to OLT), and bounds it to the maximum delay requirement D_p^{max}, which would be effective when the requested bandwidth is larger than the minimum granted bandwidth for priority p queue. Here, the estimated maximum delay is obtained based on the analysis in [65], which assumes the transmission over one wavelength and is computed per ONU i as follows:

$$D_i^{max} = (C_i + 2)T_c - A_i - C_i \frac{G_i}{\mathcal{C}_i},$$

where C_i is the number of polling cycles until the queue of ONU i is full, A_i

is the allocated transmission length (in seconds), G_i is the allocated grant (in bytes), and $\mathcal{C}_i$ is the instantaneous upstream ONU data rate. In our model, we need to approximate the maximum delay per priority queue, which should take into account that traffic can be transmitted over multiple wavelengths in any given cycle. Furthermore, the model in [65] assumed a fixed cycle time T_c^n for every cycle n (i.e., $T_c^n = T_c = 2\text{ms}$), which does not capture the dynamic nature of DBA. Thus in our model, we use the time of cycle $n-1$ for better approximation. Thus, $\mathcal{C}_i$ would be computed as $R_{i,p}/T_c^{n-1}$. Moreover, G_i in our model would be $\sum_{k=1}^{|M|} L_{i,p,k} \times \mathcal{C}$, which is the sum of all allocated transmission lengths for priority p traffic of ONU i over all wavelengths times the upstream speed $\mathcal{C}$.

A_i in our model would be the difference between the transmission end time of ONU i across all allocated wavelengths $E_{i,p}$ and the "nearest" transmission start time for priority p, denoted as $t_{i,p}^{init}$. To find $t_{i,p}^{init}$, we introduce constraints (4.18)-(4.22). More specifically, Constraint (4.18) sets $\varpi_{i,p,kh}$ to one if the start time of ONU i's priority p traffic on channel k is less than that on channel h. We need the variable $\varpi_{i,p,kh}$ so that we can determine the wavelength k over which priority p of ONU i will have the "nearest" start time, by checking that $t_{i,p,k}$ is smaller than all the other start times over all occupied wavelengths, i.e., $\sum_{h=1}^{m} \varpi_{i,p,kh} = \sum_{h=1}^{m} y_{i,p,h} - 1$. Constraints (4.19) and (4.20) handle the case where a start time is zero if the wavelength was not allocated, i.e., $y_{i,p,k} = 0$. Constraints (4.21) and (4.22) ensure that $t_{i,p}^{init}$ is set to the "nearest" start time. Finally, C_i would be $C_{i,p}$ in our model, and is obtained as follows [65]:

$$C_{i,p} \simeq \lceil \frac{S_{i,p}}{R_{i,p} - B_i^{min} \times \varrho_p} \rceil.$$

4.1.2 Tunable Transceivers

When the ONU is equipped with a tunable transceiver, it may be able to transmit on all wavelengths, but only on one wavelength at a time with tuning time ϵ. Thus, the input parameters Λ_i and $\delta_{i,k}$ would no longer required if the ONU is assumed to support all wavelengths.

In addition, a new variable would be required to keep track of the order in which a particular ONU for a specific priority is sending:

$$z_{i,pq,kh} = \begin{cases} 1 & \text{if } t_{i,p,k} < t_{i,q,h} \quad k \neq h \quad or \quad (k = h, p \neq q) \\ 0 & \text{otherwise} \end{cases}$$

Consequently, Constraint (4.5) becomes:

$$\sum_{k=1}^{|M|} y_{i,p,k} \leq |M| \quad \forall i, p, \tag{4.24}$$

with the following additional constraints to manage the variable $z_{i,pq,kh}$:

$$z_{i,pq,kh} + z_{i,qp,hk} = 1 \quad \forall i, k, h, p, q \tag{4.25}$$

$$t_{i,p,k} - t_{i,q,h} \leq \Theta \times z_{i,qp,hk} \quad \forall i, k, p \tag{4.26}$$

$$\begin{aligned} t_{i,p,k} + L_{i,p,k} + \epsilon - t_{i,q,h} \leq \Theta \times (1 - z_{i,pq,kh} + 2 \\ -y_{i,p,k} - y_{i,q,h}) \quad \forall i, k, h, p, q \end{aligned} \tag{4.27}$$

$$\begin{aligned} t_{i,q,h} + L_{i,q,h} + \epsilon - t_{i,p,k} \leq \Theta \times (1 - z_{i,qp,hk} + 2 \\ -y_{i,p,k} - y_{i,q,h}) \quad \forall i, k, h, p, q \end{aligned} \tag{4.28}$$

Note that if the ONU is equipped with multiple tunable transceivers TR, then there will be a variable per transceiver for each ONU. For example, $t_{i,p,k}$ becomes t_{i,p,k,TR_x} where TR_x corresponds to the particular used transceiver. Such modifications are needed so that an ONU is scheduled time slots on all $|TR|$ wavelengths without any overlap among the time slots. To keep the model tractable, and for consistency, we do not include the transceiver variable in the formulation.

4.1.3 Complexity Analysis

The complexity of the joint grant sizing and bandwidth/wavelength scheduling MILP problem depends on the number of ONUs $|N|$, priorities $|P|$, wavelengths $|M|$, and wavelengths supported $|\Lambda_i|$. The worst case occurs when every priority p traffic for an ONU is scheduled on all wavelengths. In such scenario, the run-time would be of $O(|M||N|^2|P|^2)$ (corresponding to $x_{ij,pq,k}$), which requires

$O(|M||N|^2|P|^2)$ constraints (corresponding to (4.11)-(4.14)). Thus, the overall complexity of the model is $O(|M||N|^2|P|^2)$. As such, this model is NP-complete and does not scale well [63].

4.2 Dynamic Wavelength and Bandwidth Allocation in OCLDN

The first key concept of the proposed scheme is to categorize the ONU requests as either Tactile T (i.e., $p = 1$), or Non-Tactile NT (i.e., $p = 2, \ldots, |P|$). The idea is to serve tactile traffic first to meet its end-to-end delay requirement, and subsequently serve the non-tactile service (cloud and legacy), while attempting to maximize the network throughput by enabling inter-channel statistical multiplexing, without impairing the latency requirements for all types of services. Our scheme also takes advantage of the ONU capability to simultaneously transmit over multiple wavelengths using a set of multiple transceivers or tunable lasers, so as to reduce the overall cycle time and schedule "contiguous" time slots using a modified version of the Water-Filling mechanism [32].

The pseudo-code of the proposed DWBA scheme is presented in Algorithm 1. Without loss of generality, one wavelength λ_1 is assumed to be initially dedicated for tactile traffic, and another one λ_2 for non-tactile traffic. However, the two get eventually shared among all traffics, depending on the needs. Thus, every ONU

Algorithm 1 Proposed DWBA Algorithm

```
Wait until all the REPORTs $(R_{1,T}, R_{1,NT}), \ldots, (R_{i,T}, R_{i,NT}), \ldots, (R_{|N|,T}, R_{|N|,NT})$ are received at the OLT, such that:
    $R_{i,T} = R_{i,1}$, and $R_{i,NT} = \sum_{p=2}^{|P|} R_{i,p}$
Compute the total requested bandwidth for Tactile and Non-Tactile $R_T = \sum_{i=1}^{|N|} R_{i,T}$ , $R_{NT} = \sum_{i=1}^{|N|} R_{i,NT}$
Compute $B_{cycle} = (T_c - |N| \times T_g) \times \mathcal{C}/8$
if $R_{NT} < B_{cycle}$ then
    $B_{cycle} = R_{NT}$
end if
if $B_{cycle} \leq R_T$ then
    Perform Limited with Fair Excess grant sizing for non-tactile requests to compute $L_{i,NT}$, and fill grants on $\lambda_2$
    Perform grant sizing using the Gated discipline to compute $L_{i,T}$ for tactile requests, and schedule the transmission lengths $L_{i,T,1}$ on $\lambda_1$, and $L_{i,T,2}$ on $\lambda_2$, using the Water-Filling scheme as in Algorithm 2
else
    $\alpha = \mathcal{L}(|N|, \mathcal{C}, d) \times \mathcal{C} \times T_c$
    if $R_T < \alpha$ then
        $B_{cycle} = 2 \times \alpha - R_T$
    else
        $B_{cycle} = R_T$
    end if
    Perform Gated grant sizing to compute $L_{i,T}$ for tactile requests and fill grants on $\lambda_1$
    Perform Limited with Fair Excess grant sizing for non-tactile requests to compute $L_{i,NT}$, and schedule the transmission lengths $L_{i,NT,1}$ on $\lambda_1$, and $L_{i,NT,2}$ on $\lambda_2$, using the Water-Filling scheme as in Algorithm 2
end if
```

reports the aggregate buffers' occupancies for tactile and non-tactile traffic via a REPORT message. In addition, tactile requests are allocated time slots $L_{i,T}$ using the Gated discipline (i.e., are allocated as requested; due to their stringent delay constraints), and non-tactile requests are granted aggregate time slots $L_{i,NT}$ using the Limited with Fair-Excess discipline so as to ensure fair bandwidth allocation [66]. Consequently, $L_{i,1,1} = L_{i,T,1}$, whereas $L_{i,NT,k}$ is further allocated to each priority queue $L_{i,p=2,\ldots,|P|,k}$ using the MDWRR intra-ONU scheduler, which has been shown to perform excellently when arbitrating different CoS queues (in our case to arbitrate the transmission of all non-tactile queues) [64].

To synchronize the simultaneous transmission of an ONU over the different channels, we first compute the length of the cycle (in bytes), denoted as B_{cycle}. B_{cycle} is then adjusted based on the size of R_{NT} (see lines 4-6) to identify the real amount of bandwidth that is allocated for non-tactile traffic. If tactile traffic is initially granted bandwidth more than the non-tactile one (see lines 7-9), the non-tactile is allocated a time slot over its dedicated wavelength(s) λ_2, whereas tactile traffic is allocated on all wavelengths using a modified version of the Water-Filling scheme, presented in Algorithm 2. This is done to ensure that non-tactile traffic is sent over its dedicated wavelength(s) before the tactile traffic is given access to all the bandwidth resources; otherwise (i.e., in lines 11-18), the non-tactile traffic is given the opportunity to exploit all wavelengths without violating the tactile delay constraint. Unlike the original version [32], the modified Water-Filling algorithm accounts for priority traffic and for boundary cases, and prevents division by zero,

Algorithm 2 Modified Water-Filling Algorithm

For every computed grant $L_{i,q}$ where q is T or NT, sort Λ_i in ascending order of $t_h^{str}, \forall \lambda_h \in \Lambda_i$
Initialize $L_{i,q,h} = 0 \quad \forall \lambda_h \in \Lambda_i$, $V_{i,q} = \varnothing$, and $k = 1$
while $\sum_{h=1}^{|\Lambda_i|} L_{i,q,h} < L_{i,q}$ **do**
  $V_{i,q} \leftarrow V_{i,q} \cup \{k\}$
  $t_{i,q,k} \leftarrow t_k^{str}$
  $k \leftarrow k + 1$
  if $|V_{i,q}| = |\Lambda_i|$ **then**
    $t_z^{str} \leftarrow t_z^{str} + (L_{i,q} - \sum_{h=1}^{|\Lambda_i|} L_{i,q,h})/|\Lambda_i|, \forall z \in V_{i,q}$
    $L_{i,q,z} \leftarrow L_{i,q,z} + (L_{i,q} - \sum_{h=1}^{|\Lambda_i|} L_{i,q,h})/|\Lambda_i|, \forall z \in V_{i,q}$
    break
  end if
  if $t_{k-1}^{str} < t_k^{str}$ **then**
    $remaining \leftarrow L_{i,q} - \sum_{h=1}^{|\Lambda_i|} L_{i,q,h}$
    $difference \leftarrow t_k^{str} - t_{k-1}^{str}$
    if $remaining > (k-1) \times difference$ **then**
      $t_z^{str} \leftarrow t_z^{str} + difference, \forall z < k$
      $L_{i,q,z} \leftarrow L_{i,q,z} + difference, \forall z < k$
    else
      $t_z^{str} \leftarrow t_z^{str} + remaining/(k-1), \forall z < k$
      $L_{i,q,z} \leftarrow L_{i,q,z} + remaining/(k-1), \forall z < k$
    end if
  end if
end while

such that t_h^{str} denotes the dynamically-updated transmission start time of λ_h, and $V_{i,q}$ denotes the set of wavelengths to be allocated for ONU i's T or NT priority traffic. For the reader's convenience, a taxonomy of the proposed DBA workflow is illustrated in Fig. 4.1.

Subsequently, the maximum number of bytes that can be sent over λ_T, α is computed. The latter is based on the maximum load $\mathcal{L}$ that would sustain the

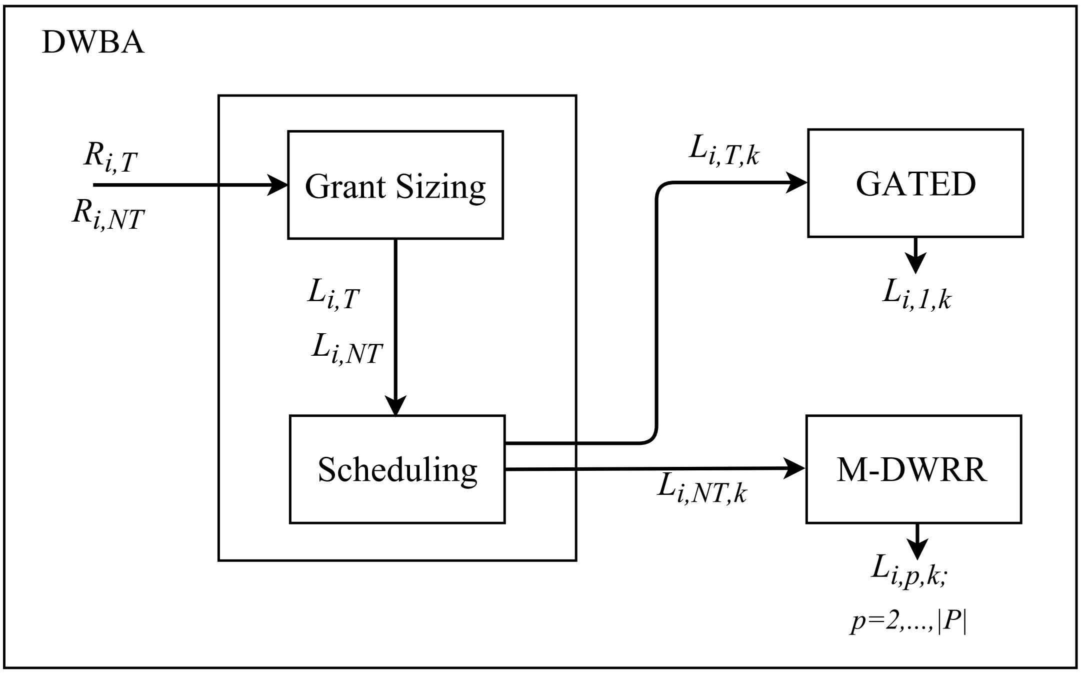


Figure 4.1: Proposed DWBA Taxonomy

tactile traffic delay constraint, which is a function of $|N|$, d, and $\mathcal{C}$ (i.e., based on a specific network configuration). As a result, the cycle length on all M wavelengths will be restricted to α; otherwise, it will be restricted to R_T.

The load $\mathcal{L}$ is obtained via bounding the end-to-end tactile packet delay for ONU i, $D_{i,1}$, by the maximum delay constraint D_1^{max} (i.e., $D_{i,1} \leq D_1^{max}$), which can be estimated as follows:

$$D_{i,1} = \overline{Q_{i,1}} + \mathcal{V}', \tag{4.29}$$

where $\overline{Q_{i,1}}$ is the average packet queueing delay, and $\mathcal{V}' = T_{trans}^{data} + 2 \times T_{proc} + RTT + T_{trans}^{ctrl}$, such that T_{trans}^{data} is the data packet transmission time in the upstream direction, T_{proc} is the packet processing time, T_{prop} is the propagation time, and $RTT = 2 \times T_{prop}$ is the round-trip time.

Using queueing theory, $\overline{Q_{i,1}}$ can be approximated for poisson-distributed packet arrivals and exponential packet distribution, as follows [67]:

$$\overline{Q_{i,1}} = \frac{\mathcal{A}_i \overline{X_i^2} + 3\mathcal{V} - \mathcal{L} \times \mathcal{V}/|N|}{2(1-\mathcal{L})}, \tag{4.30}$$

where, for a service rate $\mu_i = \mathcal{C}/(pktSize \times 8)$, the data arrival rate is $\mathcal{A}_i = \mathcal{L} \times \mu_i \times |N|$, with $\overline{X_i^2} = 2/\mu_i^2$ as the second moment of the packet transmission time, and $\mathcal{V}$ is the "server" vacation time such that:

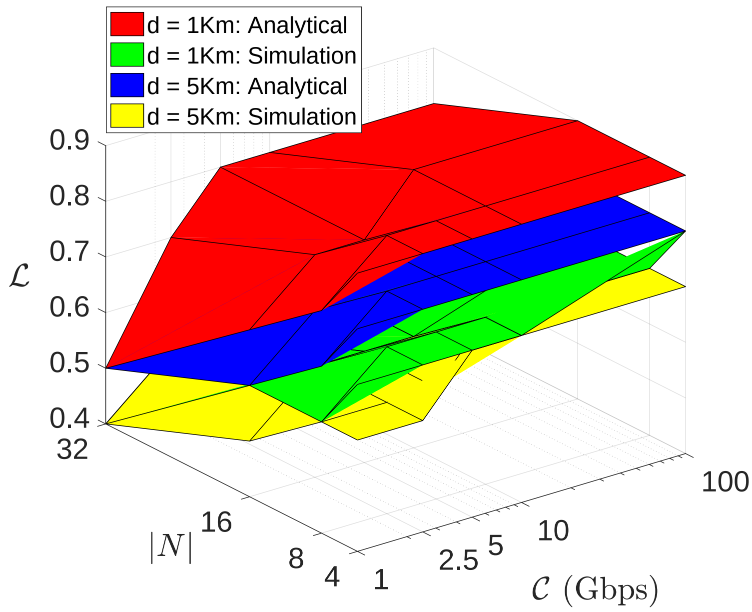
$$\mathcal{V} = (T_g + T_{trans}^{REPORT}) \times |N| + 2 \times T_{prop} + T_{proc} + T_{trans}^{GATE},$$

where T_g is the gurad time; T_{trans}^{REPORT} and T_{trans}^{GATE} are the REPORT and GATE packet transmission times in the upstream direction, respectively. Consequently, we can estimate the maximum load (line 11 of Algorithm 1) $\mathcal{L}(|N|, \mathcal{C}, d)$, under which the delay constraint of tactile traffic $D_{i,1} \leq D_1^{max}$ is always met, as follows:

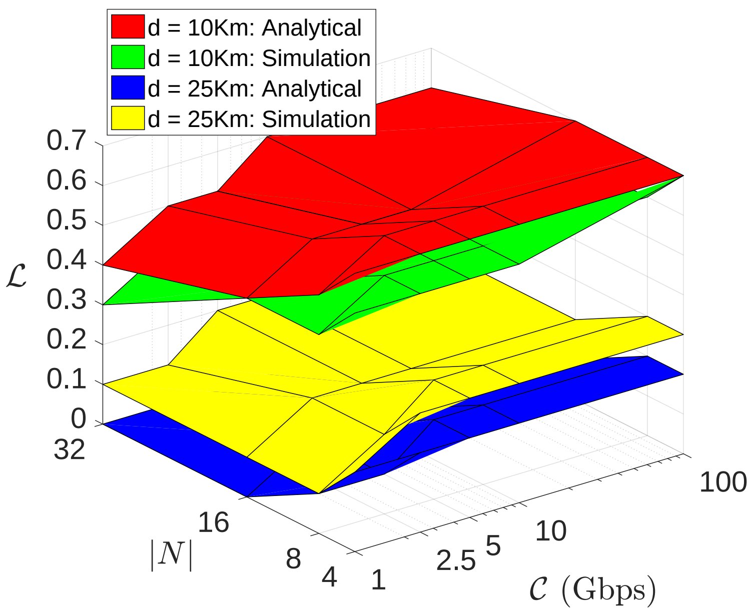
$$\mathcal{L}(|N|, \mathcal{C}, d) \leq \frac{2(D_1^{max} - \mathcal{V}') - \lambda \overline{X_i^2} - 3\mathcal{V}}{2(D_1^{max} - \mathcal{V}') - \mathcal{V}/|N|}. \tag{4.31}$$

4.2.0.1 Accuracy of Load Approximation

To test the usability of the load approximation obtained in (4.31), we compared analytical results with simulations for different network configurations. As illustrated in Fig. 4.1, in general, it can be observed that the analytical and simulation results for $\mathcal{L}$ are very comparable. However, we especially notice that for $d = 10Km$ and $25Km$, the values are much more comparable (with a difference of about 0.1 of load) than for $d = 1Km$ and $5Km$ (the difference can reach about 0.2 of load). Hence, this approximation may not be fit to be used for all configurations. In addition, the approximation can not capture the bursty nature of Internet traffic (and specially for tactile traffic [19]).



(a) $d = 1Km$, $5Km$.



(b) $d = 10Km$, $25Km$.

Figure 4.1: $\mathcal{L}$ as a function of d, $|N|$, and $\mathcal{C}$ for Poisson traffic.

Table 4.2: Maximum load $\mathcal{L}$ as a function of d, $\mathcal{C}$, and $|N|$ for Pareto traffic.

Upstream Speed (Gbps)		1				2.5				5				10				100			
Number of ONUs		4	8	16	32	4	8	16	32	4	8	16	32	4	8	16	32	4	8	16	32
Distance (Km)	1	0.2	0.1			0.3	0.3	0.2	0.2	0.6	0.3	0.3	0.2	0.6	0.6	0.4	0.3	0.7	0.7	0.5	0.4
	5	0.1	0.1			0.2	0.1	0.2	0.1	0.6	0.3	0.2	0.1	0.6	0.6	0.3	0.3	0.7	0.6	0.5	0.4
	10	0.1	0.1			0.1	0.1	0.1		0.5	0.3	0.2	0.1	0.5	0.5	0.2	0.2	0.6	0.6	0.3	0.3
	25					0.1				0.3	0.2			0.4	0.2			0.6	0.3	0.2	0.1

Therefore, we conducted a simulation study to extract $\mathcal{L}$ using Pareto-distributed traffic arrivals and packet sizes uniformly distributed between 64 and 1518 bytes; the results are reported in Table 4.2. The cells without any reported values imply that for a specific configuration, or for $d > 25km$, the tactile delay constraint can not be met. Thus, the presented values can be used as a guiding framework for network configuration and dimensioning of tactile-capable PON networks.

4.2.1 Complexity Analysis

The time complexity of Algorithm 1 is dominated by the Water-Filling performed in lines 9 and 18, which is $O(|M| \log |M|)$ as shown in [32]. Given that Water-Filling is performed only once for every ONU (either for tactile or non-tactile), the time complexity of Algorithm 1 is $O(|N||M| \log |M|)$, which is fast even for a large network.

Chapter 5

Results and Analysis

To validate the effectiveness of the proposed solutions, we conducted extensive simulations using OMNET++ [68]. T_c is set to $2ms$, T_g to 1 µs, $S_{i,p}$ to $10MB$, $\mathcal{C}$ to $10Gbps$, d to $5Km$, and $|N|$ to 8; thus $\mathcal{L}$ is set to 0.6 according to Table 4.2. Unless stated otherwise, every ONU is assumed to be equipped with two tunable transceivers.

Table 5.1: Simulation Scenarios.

Class of Service	Scenario 1	Scenario 2	Scenario 3
Constant Bit Rate (CBR)	2.52%	1.40%	0.28%
Variable Bit Rate (VBR)	5.04%	2.80%	0.56%
Best Effort (BE)	5.04%	2.80%	0.56%
Basic Cloud (CL-B)	19.35%	10.75%	2.15%
Intermediate Cloud (CL-I)	40.95%	22.75%	4.55%
Advanced Cloud (CL-A)	17.10%	9.50%	1.90%
Tactile Cloud (CL-T)	10%	50%	90%

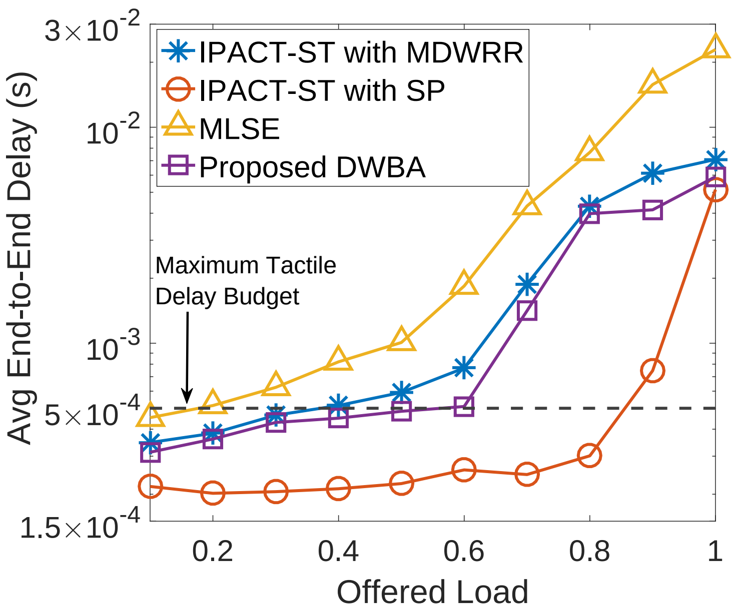
To stress-test our scheme, we consider three different simulation scenarios based on the traffic configurations in Table 5.1. Without loss of generality, to reduce the simulation time, the number of wavelength channels is set to 2, unless stated otherwise. Here, according to [8], cloud traffic is expected to account for 86% of the total access traffic, out of which 25% is basic cloud traffic, 52% is intermediate cloud traffic, and 23% is advanced cloud traffic; thus, we adopt these percentages in our simulations. On the other hand, the percentage of tactile traffic is varied between 10%, 50%, and 90% to test the robustness of our algorithm in satisfying the tactile traffic delay requirements for different arrival rates. The remaining 14% are distributed as follows: 20% are Constant bit rate (CBR), 40% are Variable bit rate (VBR), and 40% are best effort (BE) [64]. CBR traffic is modeled using Poisson with packet size fixed to 70 bytes. VBR, BE, and cloud applications can be characterized by self-similarity [69] and thus are modeled using the Pareto distribution with hurst parameter H = 0.8, and packet sizes uniformly distributed between 64 and 1518 bytes. The steering control packet is of size 64 bytes and is sent over of the downstream channel in a TDM fashion [19]. The weight percentages for the MDWRR scheme are distributed equally over the five non-tactile queues. The 95% confidence interval of the simulation results gave a $\approx 2\%$ variation, which is statistically insignificant; hence it is not shown in the figures. We use the following metrics for measuring the performance: 1) packet delay; 2) throughput; 3) and packet drop rate. For tactile traffic, we use the end-to-end $D_{i,p}$ from (4.29); whereas for non-tactile traffic $D_{i,p}$ (i.e., legacy data and cloud, where $p \geq 1$), the one-way delay is used, which is computed as follows:

$$D_{i,p} = \overline{Q_{i,p}} + T_{prop} + T_{trans}^{data} + T_{proc} + \beta T_{core}, \tag{5.1}$$

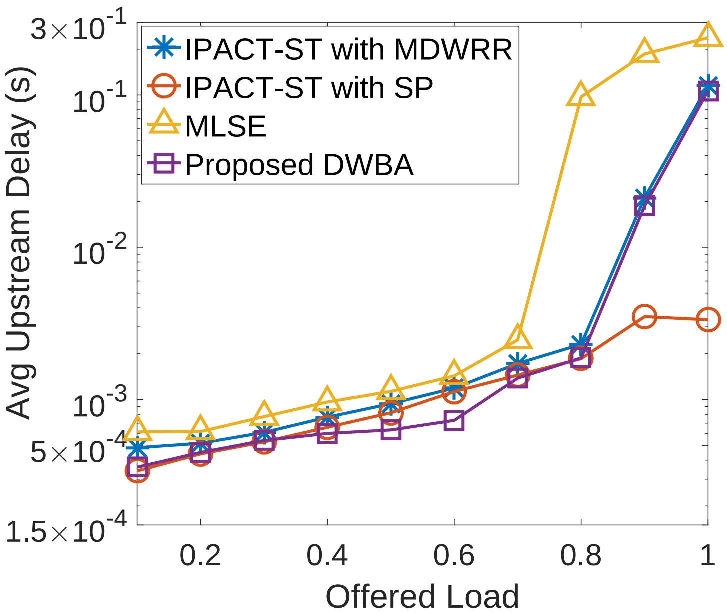
where $\overline{Q_{i,p}}$ is the average packet queueing delay, and T_{core} is the additional time incurred on cloud packets for contacting a cloud server in the core network. Namely, let ρ be the hit rate at the CDN server, i.e., the percentage of requests served by the CO's servers; thus, $\beta = \rho$ for cloud packets and $\beta = 0$ otherwise. In our simulations, we set $\rho = 0.9$ [70]; that is 90% of the incoming non-tactile cloud traffic are assumed to be served by the mini-data center, whereas the remaining 10% are fetched from the core cloud servers, which adds $3ms$ of additional delay; this value is based on the delay between Inter-route's European data centers [71]. Note that we implemented the MILP model using CPLEX [72], but we could not obtain results for the network configuration due to high computational time (more than a few hours).

5.1 Comparison with Other Schemes

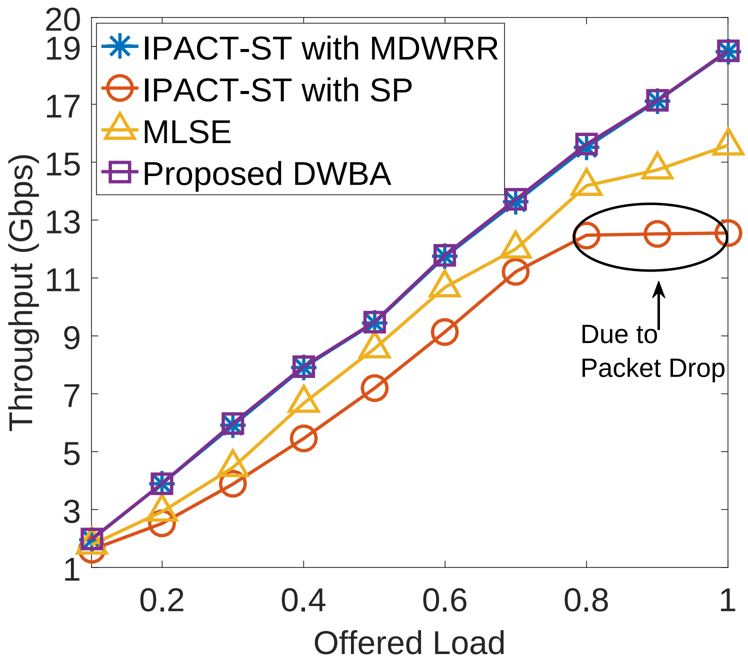
In this section, we compare the performance of the proposed DWBA scheme with other existing schemes under Scenario 2 (i.e., the "balanced" one). These schemes are the predictive allocation using MLSE [19], which is the only mechanism in the literature that supports tactile services in PONs, and the state-of-the-art IPACT-ST [29] with strict priority (SP) as benchmark, as well as IPACT-ST with MDWRR [64] as its enhanced version. In IPACT-ST with MDWRR, the tactile's queue weight is set to 0.5 and the remaining weight is distributed equally over the other traffic queues, so as to mimic the "protection of tactile traffic" and weight allocation in our proposed scheme. For IPACT-ST/MDWRR, wavelengths are selected on a *first-available-time* basis.



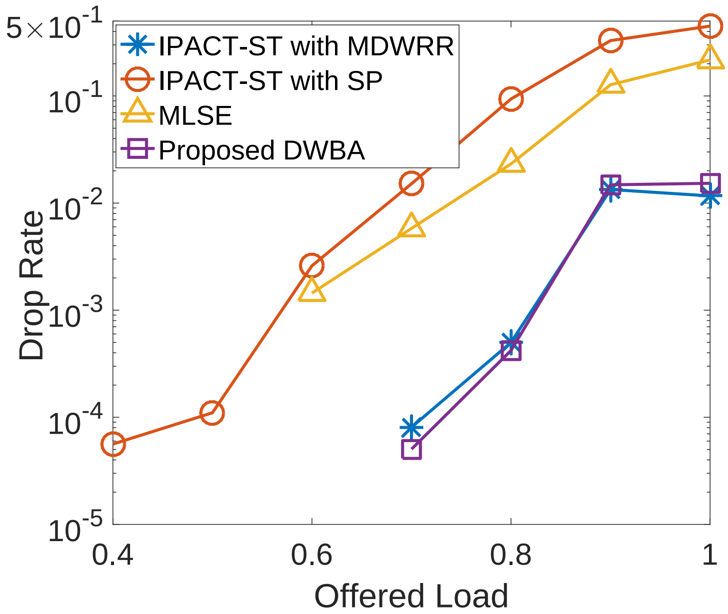
(a) Average End-to-End Tactile Packet Delay.



(b) Average Upstream Non-Tactile Packet Delay.



(a) Total Network Throughput.



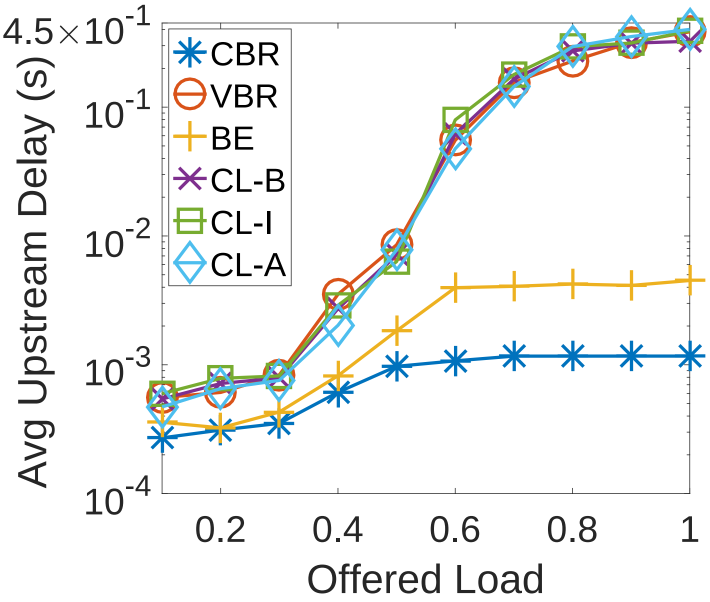
(b) Packet Drop Rate.

Figure 5.1: Comparison of DWBA with Existing Schemes.

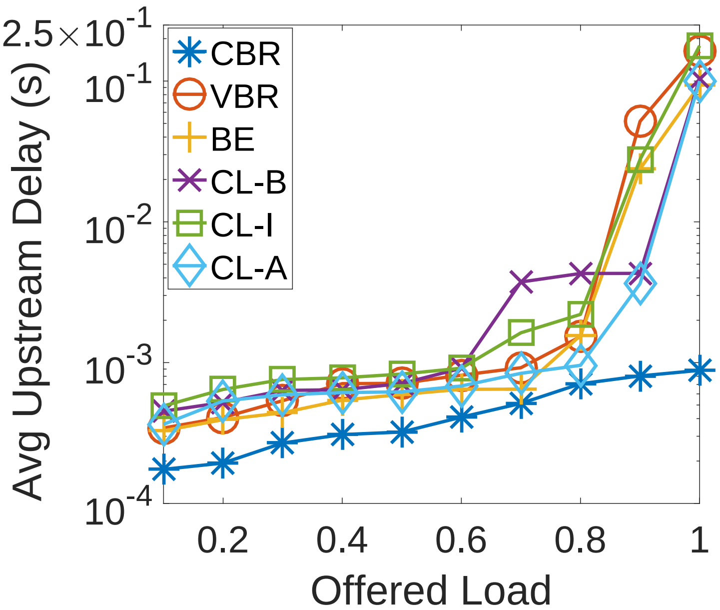
As noticed in Fig. 5.1, the predictive scheme exhibits the worst performance among all other schemes for all metrics. This is due to the shortcomings of MLSE in not being able to attain accurate prediction of requested bandwidth due to the traffic's bursty nature, which resulted in high delay, low network throughput, and high drop rate. As for IPACT-ST with SP, it is able to provide lower delay for tactile traffic compared to the other schemes, as shown in Fig. 5.1(a). This is due to the nature of SP, which prevents lower priority queues from sending traffic unless the tactile queue is emptied. However, this penalizes lower priority queues and downgrades their performance as depicted in Figs. 5.1(b), 5.1(a), and 5.1(b), where the low non-tactile packet delay comes at the expense of low throughput and high packet drop rate. For IPACT-ST with MDWRR, it exhibits a behaviour similar to the proposed scheme in terms of network throughput, packet drop rate, and non-tactile delay, which is a result of the adaptively set weights in MDWRR. However, our DWBA scheme outperforms IPACT-ST in terms of lower tactile packet delay, and support for higher loads. This is due to the ability of the proposed DWBA scheme is enabling inter-channel statistical multiplexing, meanwhile protecting the tactile traffic via the parameter α.

All these results highlight the ability of the proposed scheme in outperforming other benchmark and state-of-the-art schemes, via supporting tactile services at higher loads, meanwhile attaining high network utilization, and meeting the QoS requirements for all types of services.

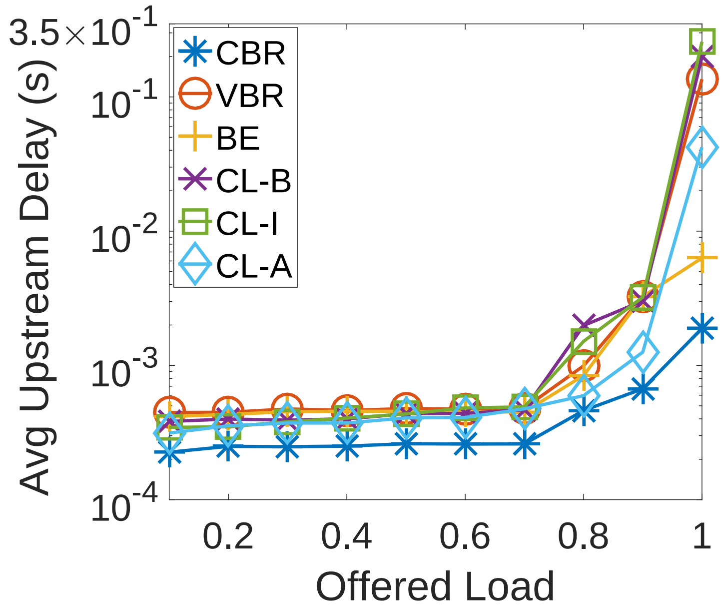
5.2 DWBA Evaluation for Different Scenarios



(a) Scenario 1

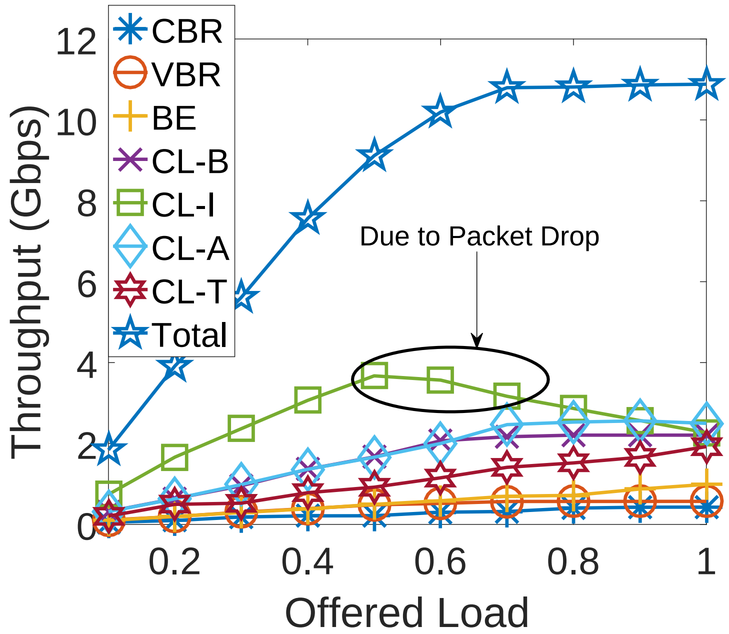


(b) Scenario 2

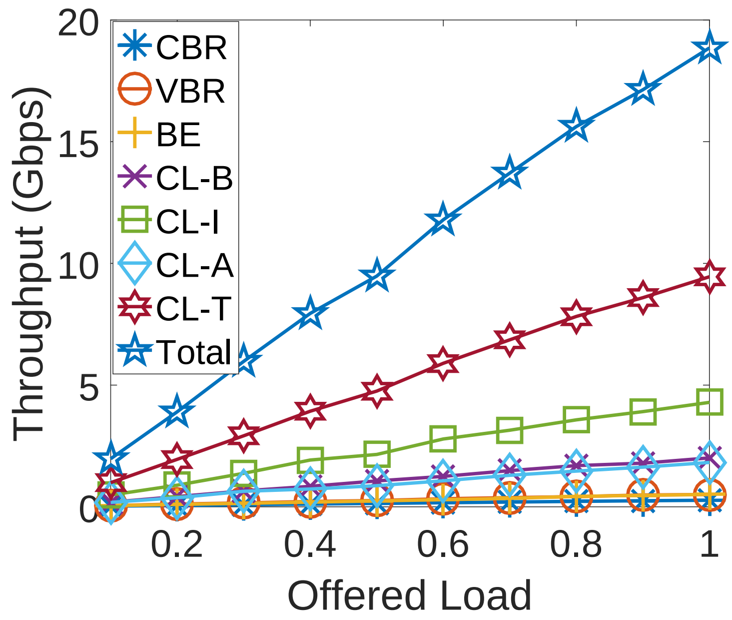


(a) Scenario 3

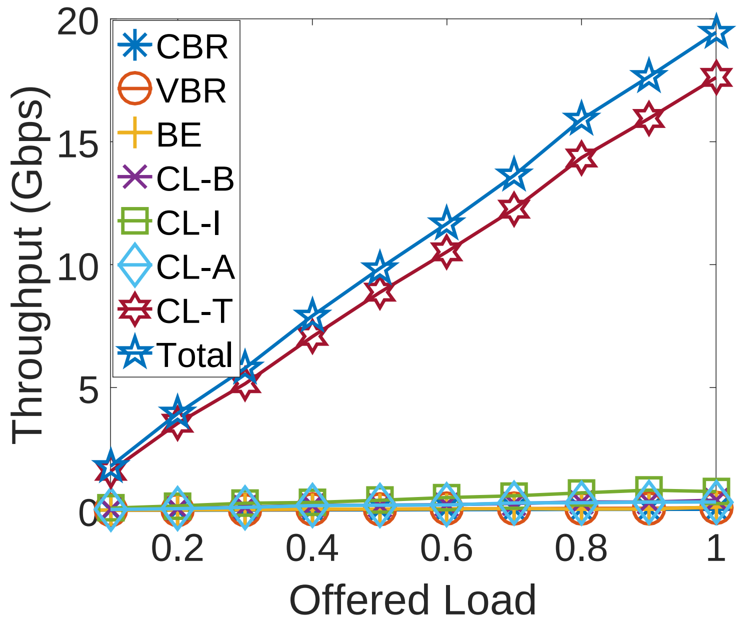
Figure 5.2: Average Upstream Packet Delay.



(a) Scenario 1



(a) Scenario 2



(b) Scenario 3

Figure 5.3: Network Throughput.

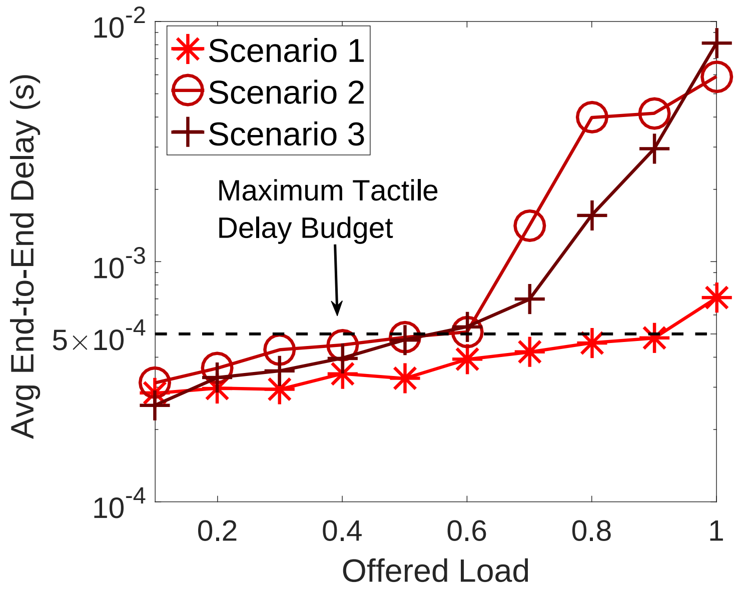


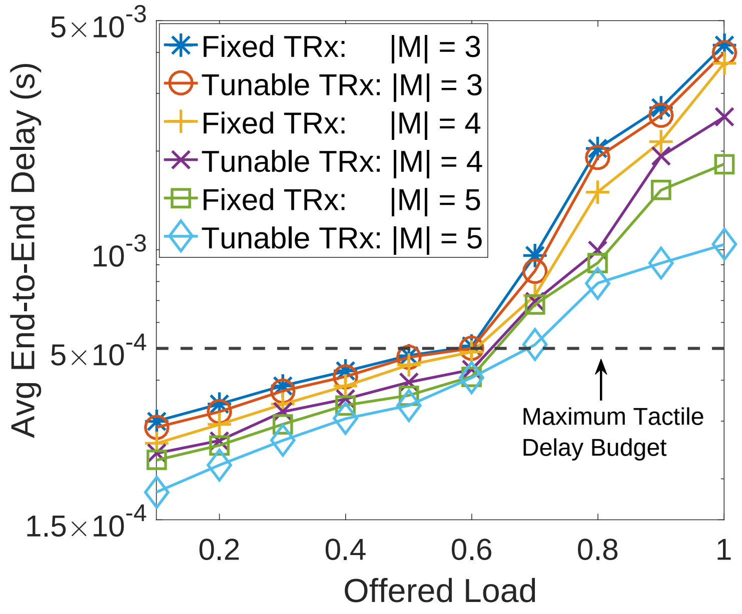
Figure 5.4: Average End-to-End Tactile Packet Delay.

Figs. 5.2, 5.3, and 5.4 show the average upstream packet delay and network throughput for all traffic classes under all scenarios, as well as the end-to-end average packet delay for tactile traffic, respectively. We notice how for Scenario 1 where the tactile traffic's percentage is 10%, the stringent 0.5 ms tactile delay is met for all network loads. The reason behind this excellent behavior is that the ONUs are granted bandwidth for tactile traffic equal to their requests. As such, since with Scenario 1 the amount of incoming tactile traffic is small, the queuing delay will be minimal. As for the other traffic classes, their delays are met up to a high network load (i.e., 0.7), since the allowed bandwidth for non-tactile traffic is limited by α. Thus, higher percentages of non-tactile traffic will be subjected to higher delays at high network loads. We also observe in Fig. 5.2(a) that the BE traffic experiences lower delay than the cloud and VBR traffics. This is due to how MDWRR is able to satisfy the BE traffic in the first scheduling pass due to its low traffic rate. In contrast, even after the distribution of the remaining bandwidth over the other unsatisfied higher priority queues, big chunks of these higher priority queued packets will not be served in the current cycle. As noticed in Fig. 5.3(a), when the network load exceeds 0.5, the throughput rate is around 50%. This is due to the fact the DWBA aims at primarily meeting the delay constraint of tactile services by protecting its wavelength from being used by the high-loaded non-tactile traffic, at the expense of suboptimal network throughput. In Scenario 2 where the tactile traffic's percentage is 50%, the delay is met up to load 0.6. This complies with the network configuration as per Table 4.2, and shows the ability of the DWBA to meet the delay requirements, by having tactile and non-tactile services each using one specific wavelength without sharing, due to their traffic loads. Consequently, the average delay of tactile traffic will be similar to having a dedicated wavelength that keeps this traffic protected from the other traffic classes. The delays of cloud and data services are met up to a load of 0.9, which is near optimal.

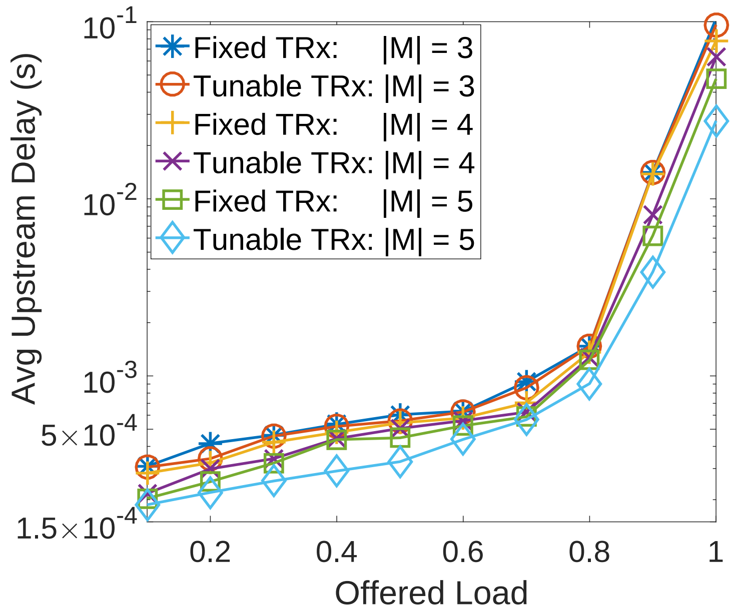
In Scenario 3 where tactile traffic's percentage is 90%, the delay is still met up to load 0.6, which still complies with the network configuration per Table 4.2. However here, even when tactile traffic's percentage is dominant, tactile services can use the non-tactile wavelength(s) as needed so as not to compromise its stringent delay requirement, thereby exploiting the inter-channel statistical multiplexing aspect of OCLDN. More importantly, our scheme is able to permit the latter

without compromising the requirements of all other types of traffic, which are all met up to a load of 0.9. This is due to the fact that non-tactile services occupy a very low proportion of the total generated traffic, and thus the requested bandwidth will not exceed the granted bandwidth.
We also notice that in both Scenarios 2 and 3, as shown in Fig. 5.3(a) and 5.3(b) respectively, a high throughput rate of 90% is achieved at high loads. This is due to the fact that tactile traffic is granted time slots using the Gated scheme, and it exploits inter-channel statistical multiplexing to maintain its performance. On the other hand, the employed scheduling scheme is able to satisfy the demands of all other traffic types regardless of their loads. This is due to the employed MD-WRR intra-ONU scheduling mechanism, which adaptively and fairly allocates the bandwidth among all traffic types.

Finally, we study the performance of our scheme for higher number of wavelengths, i.e., with $|M| = 3$, 4, and 5, such that an ONU is equipped with either two fixed or two tunable transceivers under Scenario 2. As observed in Fig. 5.5, as $|M|$ increases, the delays for both tactile and non-tactile packets decrease, due to having less ONUs sending on the same wavelength. In addition, as $|M|$ increases, installing tunable transceivers yields lower delays than the fixed ones, yet at the expense of higher cost. More importantly, as observed in Fig. 5.5(a), even though deploying more wavelengths (e.g., $|M|= 5$) can enhance the performance of tactile delay, it can be seen that the gain may not be worth the investment (e.g., the supported load for $|M|= 5$ is 0.7, vs. 0.6 for $|M|= 3$). Moreover, the



(a) Average End-to-End Tactile Packet Delay.



(b) Average Upstream Non-Tactile Packet Delay.

Figure 5.5: Tactile and Non-Tactile Delays for $|M| = 3, 4, 5$.

gain in the non-tactile performance is minimal, as shown in Fig. 5.5(b). Thus, interestingly, deploying more channels (which increases the network cost) may not necessarily result in better network performance.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

In this work, we proposed OCLDN, a new programmable and scalable optical cloud distribution network architecture that enables the delivery of killer cloud services, including Tactile Internet in a fast, efficient and cost-effective manner. We formulated the grant sizing and scheduling in OCDLN as a MILP optimization problem, and then proposed a new dynamic wavelength and bandwidth allocation scheme that employs the Water-Filling technique and an advanced intra-ONU scheduling discipline to meet the QoS requirements for all types of services regardless of their arrival rates and distribution. Extensive simulations validated the effectiveness of the proposed solution versus existing schemes, and demonstrated its ability to meet the stringent QoS requirements for all types of cloud and legacy data services. Our solution has the promise to be employed by ISPs, so as they deliver killer cloud services closely to the users and meet their stringent QoS demands, as well as add new sources of revenues.

6.2 Future Work

Our proposed work leaves some interesting and potential issues that need further research and investigation, as listed below:

- In Scenario 1, meeting the strict delay of Tactile Internet traffic required a sacrifice in terms of network throughput. Future work involves finding the best compromise between the throughput and delay requirements.
- Our scheme requires small distances between ONUs and the steering/control server. Supporting Tactile Internet for larger distances, such as in LR-PON, requires further investigation.
- Introducing an energy-efficient version of the proposed DWBA scheme that reduces power consumption is an interesting extension of this work.

Appendix A

Acronyms

AF	Assured Forwarding
APON	ATM PON
AR	Augmented Reality
ATM	Asynchronous Transfer Mode
BE	Best Effort
BPON	Broadband PON
CATV	Community Antenna Television
CBR	Constant Bit Rate
CDN	Content Delivery Network
CO	Central Office
CORD	Central Office Re-Architected as a Data Center
CoS	Classes of Services
DBA	Dynamic Bandwidth Allocation
DC	Deficit Counter
DiffServ	Differentiated Services
DSL	Digital Subscriber Line
DWBA	Dynamic Wavelength and Bandwidth Allocation
DWRR	Deficit Weighted Round Robin
EF	Expedited Forwarding
EHR	Electronic Health Records
EPF	Earliest Packet First
EPON	Ethernet PON
FE	Fair-Excess
FSAN	Full Service Access Network
GEM	GPON Encapsulation Method
GPON	Gigabit PON
HDTV	High-Definition Television
HOL	Head Of Line
HSI	Human-Machine Interface
IaaS	Infrastructure-as-a-Service

IoT	Internet of Things
IPACT	Interleaved Polling with Adaptive Cycle Time
IPTV	Internet Protocol Television
ISP	Internet Service Provider
LR-PON	Long-Reach Passive Optical Network
LQF	Longest Queue First
M2H	Machine-to-Human
M2M	Machine-to-Machine
MAC	Medium Access Control
MAN	Metropolitan Area Network
M-DWRR	Modified Deficit Weighted Round Robin
MILP	Mixed-Integer Linear Programming
MLSE	Maximum-Likelihood Sequence Estimation
MPCP	Multi-Point Control Protocol
MSD	Multiple Scheduling Domain
M-SFQ	Modified Start-Time Fair Queuing
NFV	Network Functions Virtualization
NG-EPON	Next-Generation Ethernet Passive Optical Network
NG-PON	Next-Generation PON
OCLDN	Optical Cloud Distribbution Network
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
P2MP	Point-to-MultiPoint
P2P	Point to Point
PaaS	Platform-as-a-Service
PON	Passive Optical Network
QoS	Quality of Service
RR	Round Robin
RTT	Round Trip Time
SaaS	Software-as-a-Service
SDN	Software-Defined Networking
SP	Strict Priority
SSD	Single Scheduling Domain
TDM	Time-Division Multiplexing
TWDM	Time and Wavelength Division Multiplexing
VBR	Variable Bit Rate
VoD	Video on Demand
VoIP	Voice over Internet Protocol
WA	Wavelength Agile
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing

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