photonics

Article

5G-Enabled Tactile Internet Resource Provision via Software-Defined Optical Access Networks (SDOANs)

Elaiyasuriyan Ganesan [1], I-Shyan Hwang [1,*], Andrew Tanny Liem [2] and Mohammad Syuhaimi Ab-Rahman [3]

[1] Department of Computer Science and Engineering, Yuan Ze University, Taoyuan 32003, Taiwan; s1069107@mail.yzu.edu.tw
[2] Department of Computer Science, Universitas Klabat, Manado 95371, Indonesia; andrew.heriyana@unklab.ac.id
[3] Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Build Environment, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia; syuhaimi@ukm.edu.my
* Correspondence: ishwang@saturn.yzu.edu.tw

Abstract: Emerging research trends in smart healthcare, smart manufacturing, and Industrial Internet-of-Things (IIoT) applications are based on 5G services, which can achieve ultra-reliable and low-latency communication networks. In such fields of application, haptic applications have gained importance. The invention of 5G wireless communication networks and advances in Tactile Internet (TI) technology, which provides controlled communications through the transmission of touch and actuation in real-time, have been envisioned as promising enablers of TI services. This study introduces TI-based smart hospital healthcare applications to enhance the alignment of services provided to patients. The existing telesurgery system has high communication delay and overhead, which limit its applicability. To alleviate these problems, we analyze and provide insights into the communication architecture for 5G-enabled low-latency telesurgery in a smart hospital. We then propose a new TI-software-defined optical access networking (TI-SDOANs) framework in Next-Generation Passive Optical Network 2, which includes cloud-based human-to-machine steering servers and supports multiple cloud-based applications. We further propose the implementation of an effective TI-dynamic wavelength and bandwidth allocation (TI-DWBA) resource provisioning scheme that meets the quality of service requirements of TI services. Simulation results show that the proposed scheduling schemes can significantly improve the Quality of Service (QoS) performance in terms of the packet delay, jitter, throughput and packet drop.

Keywords: IIoT/5G; TI-SDOANs; TI-DWBA; QoS

Citation: Ganesan, E.; Hwang, I-S.; Liem, A.T.; Ab-Rahman, M.S. 5G-Enabled Tactile Internet Resource Provision via Software-Defined Optical Access Networks (SDOANs). *Photonics* **2021**, *8*, 140. https://doi.org/10.3390/photonics8050140

Received: 16 March 2021
Accepted: 20 April 2021
Published: 23 April 2021

1. Introduction

The Tactile Internet (TI), which supports 5G technology, is considered to be an evolved form of the Internet of Things (IoT). The shift towards IoT technology creates a new paradigm in which "anything" can be remotely accessed and/or controlled. TI is a telecommunications network that enables human users to immersively control and manipulate both real and virtual remote objects or machines. The term TI was coined by G. Fettweis, in 2014, in the context of the vision of 5G technology-enabled IoT, which is starting to be rolled out around the world [1]. Currently, the IEEE 1918.1 standards working group defines "Tactile Internet" as a network (or network of networks) for "remotely accessing, perceiving, manipulating, or controlling real or virtual objects or processes in perceived real-time by humans or machines" [2], and some primary applications considered are immersive virtual/augmented reality (VR/AR), teleoperation, and live haptic-enabled automated driving.

TI is expected to enable a plethora of new opportunities and applications that will transform our lives and economy [3]. Further, TI will provide a true paradigm shift from content-delivery to skill-set delivery networks, thereby causing a revolution in every section of society [4]. To adequately support TI applications, the most important design objective for network infrastructure is a very low end-to-end latency of less than 1 ms [5]. More specifically, according to the IEEE P1918.1 working group on TI, a teleoperation scenario includes the following requirements: guaranteed ultra-high reliability of 99.999% (haptic, video, and audio); a network bandwidth of 100–500 packets per second for haptic control and feedback; and bandwidths of 1–100 Mb/s and 5–512 kb/s for video and audio channels, respectively, between the teleoperator and operator [6]. Moreover, the authors of [7] point out that there is an overlap in the concepts and technologies related to IoT, 5G, and TI, such as ultra-low latency requirements, guaranteed availability, human-to-human (H2H) communications, machine-to-machine coexistence (M2M), high-bandwidth requirements, and the need for secure network infrastructure with integrated edge computing intelligence.

The emerging TI potentially precedes a shift from content-oriented communications to steer/control-based communications that empower humans to control both real and virtual objects via wired and wireless channels. The emergence of TI is beginning to fuel the next stage in the evolution of wired and wireless communication infrastructures: the wide core network, metro-access network, enterprise local area network, and personal area network [8]. The rapid growth of IoT and TI brings new challenges in network resource allocation on the Internet, particularly in the “last-mile” access network, which has been recognized as a major bottleneck region of the internet for a long time [9]. The regular internet facilitates voice and data communications and provides a medium for audio and visual transport. However, TI enables primary applications, haptic communications [10], and provides a medium for real-time touch and operation, that is, the ability to transfer haptic control over the Internet, in addition to non-haptic control and data [11].

Among the passive optical network (PON)-based networks, Ethernet passive optical network (EPON) is a prominent solution for providing diverse services. PON can overcome the bandwidth limitations of the last mile bottleneck problem in access networks [12]. EPON has been standardized in the IEEE 802.3ah (1G-EPON) and IEEE 802.3av (10G-EPON) standards [13]. The single access distribution network (ODN) includes extensive research to find practical solutions for future access networks that require higher bandwidth and low delays to accommodate mobile, residential and commercial services. The NG-PON2 is expected to be a multi-service infrastructure that enables network operators to break into multiple service sites. These approaches often focused on multi-wavelength-based PON. Typically, time and wavelength division multiplexing (TWDM-PON) with four wavelengths has a capacity of 40 Gbps [14,15]. The project has been selected for the NG- PON technology in the NG-PON2 standard (ITU-T G.988.1) [16], and in addition 25-G and 50-G in NG-EPON of IEEE 802.3ca. [17]. Moreover, TWDM-PON is expected for many service platforms, offering the possibility of data rates of more than 10 Gb/s per channel to enable low-latency services for mobile, business, residential, M2M, TI services. [18]. More specifically, to meet the low delay and higher resource requirements of tactile traffic, a vital research area for TWDM-PON is the allocation of bandwidth flexibly through the dynamic bandwidth allocation (DBA) scheme. In these studies, we proposed dynamic wavelength and bandwidth allocation (DWBA) as a method to implement in optical line terminal (OLT) that dynamically allocates channel bandwidth between multiple wavelengths based on time points for data transmission in the upstream direction. Each optical network unit (ONU) can transmit data at the allotted wavelength during the allotted time slot, and DWBA helps avoid any conflict between different ONUs in terms of data transmission.

A promising network architecture beyond 5G and B5G wired and wireless integrated access networks combines passive optical networks (PONs) with wireless access networks to inherit the benefits of both optical access and wireless access [12,19]. It benefits of the optical access network can give competent bandwidth, transmission quality and stability, at the same time wireless access enables pervasive connectivity with high flexibility and cost-effectiveness. With the tremendous growth of mobile data traffic, increasing radio access technologies (RATs), and high cell density leading to 5G networks, the barrier is gradually shifting from radio interface to backhaul segment [20]. To address this, a possible solution is to share the high-capacity and reliable OAN infrastructure already widely used in a cost-effective way to block backhaul access, which was originally intended for standard broadband access [21,22]. This can be facilitated by OANs that are able to seamlessly integrate a multi-radio access technology (Wi-Fi, 5G, etc.) front-end network is supported for human-centric and tactile applications on the single infrastructure [23]. Furthermore, the emerging software-defined networking (SDN) topology is likewise important in the applications for OANs. The integration of SDN and OAN gives rise to so-called software-defined optical access networks (SDOAN). Recently, SDN has become a potential research interest in several fields, including education, industry, and banking [24]. SDN provides operators with improved resource provisioning, flexibility, and lower operational expenditures. SDN focuses on separating the control and data plane functions of the network, where the control plane determines the packet flow through the network, and maintains, controls, and programs the data plane. Furthermore, SDN aims to use the centralized programmable network model used by the Open Flow protocol to modify the SDN mechanism in the network.

In this paper, we propose a 5G-enabled Tactile Internet SDOAN (TI-SDOAN) smart hospital resource provision to improve system performance. In particular, we give details of the first attempt to address this need through 5G-based low-delay telecommunications remote surgery. Subsequently, we propose a new architecture that enables internet service providers to construct a cloud-based high-speed network and an agile, programmable, and scalable SDOAN. To support the low-latency requirement of tactile services in SDOAN, we propose a new Tactile Internet-DWBA scheme that enables the protection of tactile services by dedicating the upstream wavelength(s) to improve Quality of Service (QoS)/quality of experience (QoE) performance. Therefore, the TI-SDOAN-based-smart hospital solution covers everything from hospital management and digital storage systems of medical information to the infrastructure construction of wired and wireless networks and data centers. Therefore, smart healthcare is one of the best environment candidates compared to other applications, where TI applications are expected to be used, in the department of healthcare. The most important aspects of the TI applications include telediagnosis, telesurgery, and telerehabilitation. The major impacts of the smart hospital system are time and cost-effectiveness [25].

The main contributions of this paper are as follows:

1. We illustrate and highlight 5G-URLC based on the efficient low latency (<1 ms) and highly reliable (99.999 percent) telesurgery architecture is proposed.
2. A new Software-Defined (SD) enabled cloudlet-based TI-SDOAN architecture and operational method for TWDM-PONs in which SD solutions manage the dynamic resource allocation of various resources in an SD programmed process.
3. To enable streamlined management of composite PON systems, the proposed SDOAN is enhanced to the OLT and ONU-AP architectures. The novelty of our work is compared to similar previous studies [26,27]. This paper focusing on the SDN-based traditional EPON architecture and proposed the dynamic bandwidth allocation using the IPACT DBA. The IPACT DBA has not supported the Tactile internet and our work is supported TI traffic and different traffic distribution and the SDN dynamically controls the active wavelengths. Further, our proposed work is based on multi scheduling-PON (MSD-EPON) mechanism in IEEE 802.3ca based-EPON.
4. To reduce the end-to-end delay and improve the QoS requirements, an adaptive TWDM-PON SD-TI dynamic wavelength bandwidth allocation (DWBA), and time management system (SD-DWTS) are presented.
5. Finally, the difference between non-SD and our proposed SD-enabled TI-SDOAN architecture and mechanism are shown in Table 1.

Table 1. Comparison of Tactile Internet-software-defined optical access networking (TI-SDOANs) and non- software-defined networking (SDN) architecture and operations in time and wavelength division multiplexing (TWDM-PON)

	Non-SD Architecture [9,19,28]	**Proposed TI-SDOAN Architecture**
A change in the standard PON configuration is required	Yes	Yes
Require SD controller and SD-agent	No	Yes
Discovery and registration	MPCP	MPCP and OpenFlow messages
ONU wavelength tuning	Modified MPCP	OpenFlow messages
ONU-AP transmission link-rate tuning	Modified MPCP	OpenFlow messages
DWBA	Yes	Yes, Programmable
Deployment can be rearranged dynamically	No	Yes

The rest of the paper is organized as follows: Section 2 is an overview of related work. Section 3 proposes the 5G-enabled low-latency telesurgery communication architecture and mechanisms. Section 4 discusses the proposed scheme and its mechanism. Section 5 describes the simulation and evaluates system performance. Section 6 presents conclusions and scope for future work.

2. Related Work

In the literature, SDOAN technology has been implemented with various wireless technologies such as WLAN, 5G, long term evolution (LTE) (i.e., wired and wireless converged access network). However, the key requirement for any process is to guarantee QoS. For example, the convergence of GPON and LTE with high capacity and QoS services and the advantage of the bandwidth of the optical network and mobility features of wireless communications and QoS mapping between these two networks is explored in [29]. In another similar study, the authors of reference [30] investigate the performance of fiber wireless integrated architecture WLAN (5G with WiFi) and XGPON. The proposed approach is to improve the QoS scheme in different types of services with the help of the highest cost first (HCF) algorithm, which leads to reduced upstream latency for delay-sensitive applications. In Ref. [31], the complete and systematic overview of the future evolution of passive optical access networks and multiplexing techniques are presented. For software-defined optical networks (SDON) subdomain access, the networks provide an overview of the access network challenges that SDN can address [23] and comprehensively survey studies that examine the SDN paradigm in optical networks are described as [32]. Furthermore, the adaptive flexible functional split of 5G networks and the resource availability in the optical access network and the accurate forecasting of the available bandwidth of the real-time functional split techniques are studied [33]. The author H. Yang et al. [34] investigate the software-defined ubiquitous datacenter optical interconnection (SUDOI) architecture and operations. Datacenter networks combine state-of-the-art server units with specialized networking technologies to process and store large amounts of data which is widely used to provide commercial and “cloud” services for social media applications. The author [35] recently proposed the work RT-Telsug (real-time network architecture on telesurgery system) based on the efficient TI and using SDN, fog, cloud infrastructure. Moreover, the detailed studies of the 5G-based tactile internet future directions [36–38] and telesurgery robotic systems are studied in [39,40]. Finally, the functionality of TWDM-PON technology with resource allocation algorithms (DWBAs), also known as TI, is explored here [9,19] and SDN-based detailed TWDM-PON architecture is described [41].

3. 5G-Enabled Low Latency TI-Telesurgery Architecture

Practical surgical robot systems first appeared in the early 1990s. The first commercial surgical method, ZEUS, was produced by Computer Motion Inc. Madhani et al. [39] developed the silver and black falcon. In 1998, the prestigious Da Vinci Surgical System by Intuitive Surgical Inc. (https://www.intuitive.com/en-us, accessed on 10 February 2021), at the

Massachusetts Institute of Technology [40]. The telesurgery system connects patients and surgeons using a wired and wireless network and a robotic system. In Figure 1, we present the 5G-enabled telesurgery architecture of a TI communication system, which mainly consists of three domains: the master domain; network domain; and slave domain.

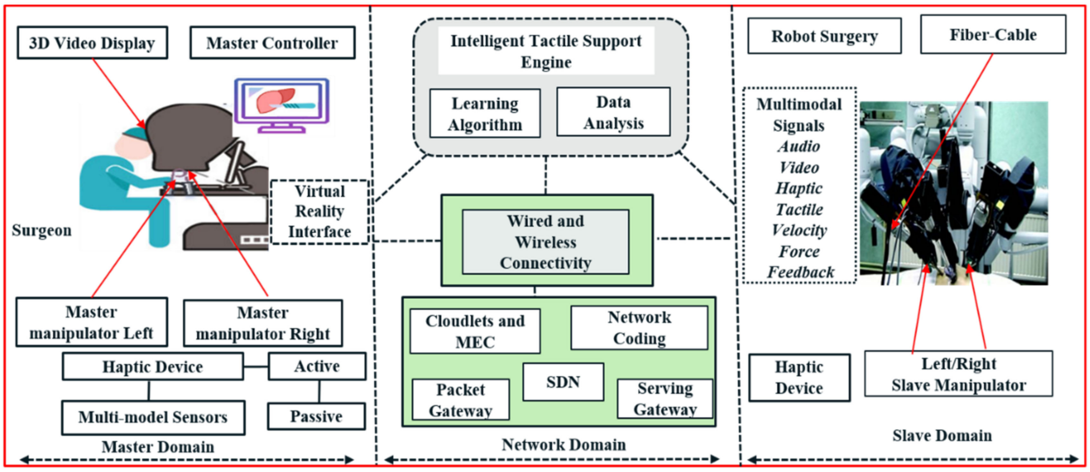


Figure 1. Smart hospital 5G-enabled low latency-tactile internet telesurgery architecture [36,37,42,43].

3.1. Master Domain

The master domain generally consists of two main components: the human operator and human–system interface (HSI), among other components. A surgeon communicates with the HSI to send control commands to the operating robot in the slave domain. The main functionality of the human operator is the surgeon to operate on the remote patient. The HSI consists of a high-definition HD video display monitor, foot pedals, and left and right master manipulators and the surgeon sends commands to a surgical robot via HSI. The HSI-master console is composed of a haptic device for position–orientation input, video display, voice, feedback, and haptic feedback output [36]. In particular, haptic devices are used to touch, feel, and manipulate three-dimensional objects in virtual environments and teleoperated systems. The master control domain controls the remote operation of the slave domain via command signals and these surgeon input signals are converted to haptic input by HSI using different techniques. Furthermore, in general, haptic devices are categorized into active (actuators, software) and passive (physical objects) types. Therefore, the master domain telesurgeon will be connected to the surgical robot by a reliable high-speed communication network that carries real-time manipulation commands and multimodal sensor data.

3.2. Network Domain

This domain is configured as transmission between the master domain and slave domain and this transmission needs a highly responsive and highly reliable connection to transmit real-time physical sensation data. The network domain generally consists of a tactile internet support engine; wired and wireless connectivity; base stations and an SDN, cloudlet/MEC packet gateway (PGW); and serving gateway (SGW) network coding.

3.2.1. Tactile Internet Intelligent Engine

This TI- engine provides artificial intelligence and a knowledge base, and medical data analysis plays a key role in stabilizing the system.

3.2.2. Wired and Wireless Connectivity

The master and slave domains are communicated through a bilateral communication link in a network domain. Telesurgery grade end-to-end latency is generally needed in motion control for smart hospitals; however, it is most often realized through a wired connection. Therefore, the 5G ultrareliable and low-latency communication (URLLC)-supported TI imposes an ultra-round-trip delay of the order of 1 ms between the primary (master) and secondary(slave) domains. However, it is capable of achieving a packet delivery reliability of 0.99999 on the TI, and thus an effective execution of a telesurgery process [38]. Furthermore, the list of utility events for the IEEE 1918.1 basic standard is as follows and Table 2 summarizes the performance requirements and traffic characteristics of utility events: teleoperation, immersive virtual reality, physical vital signs and live multimedia streaming. The teleoperation system QoS requirements and the capabilities vary considerably based on the operation of the remote environment in which the system remote operator is located. For example, a highly dynamic environment to play the telesurgery based online game (soccer) is the transmission of haptic signals, which requires a delay of 1–10 ms and a medium dynamic environment "telesurgery and telerehabilitation" with a latency requirement of haptic data exchange is 10–100 ms [2,44].

Table 2. Communication QoS requirements for TI Use cases (Telesurgery).

Use Cases	Traffic Types	Reliabilty (%)	Latency (ms)	Jitter (ms)	Packet Loss Rate	Data Rate
Teleoperation (Master→Slave) [2]	Haptics	99.999	1–10 (High dynamic Environment	-	-	1–4 pkts/s
			10–100 (medium dynamic Environment)	-	-	100–500 pkts/s
Teleoperation (Slave→Master) [2]	Video Audio Haptic Feedback	99.999 99.9 99.999	10–20 10–20 1–10	- - -	- - -	1–100 Mbps 5–512 Kbps 1–4 kbps
Telesurgery [44]	Haptic Feedback	Force Vibration	3–10 <5.5	<2 <2	$<10^{-4}$ $<10^{-4}$	128–400 kbps 128–400 kbps
Live-Multimedia stream [44]	2D Camera 3D Camera Audio	- - -	<150 <150 <150	3–30 3–30 <30	$<10^{-3}$ $<10^{-3}$ $<10^{-2}$	<10 Mbps 137 Mbps–1.6 Gbps 22–200 kbps
Physical Vital Signs [44]	Blood Pressure Heart Rate ECG	- - -	<250 <250 <250	- - -	$<10^{-3}$ $<10^{-3}$ $<10^{-3}$	<10 kbps <10 kbps 72 kbps
Immersive Virtual Reality (Master→Slave User→IVR System) [2]	Haptic Feedback	99.9 99.999	<5	-	-	1–4 k pkts/s 100–500 pkts/s
(Master→Slave) [2]	Video Audio Haptic Feedback	99.999 99.9 99.9	<10 <10 1–150	- - -	- - -	1–100 Mbps 5–512 kbps 1–4 k pkts/s

3.2.3. Cloudlet

This is used to provide resource-intensive and interactive value-assisted services to the telesurgery procedure by providing powerful computing resources to end-users and reducing the latency compared to that of traditional infrastructure. The communication between surgeon operators and slave machines in the same wired or wireless access network, data processing, and exchange can be expedited by harnessing edge cloudlets deployed at end users.

3.2.4. SDN and Network Coding (NC)

This is a controller that aims to make the network agile and flexible. SDN provides an architectural framework in which the control plane and data plane are decoupled and enables direct programmability of network control through a software-based controller [45]. NC can offer a new paradigm as a promising technique to effectively manage communication networks, generating numerous research interests in wireless and wired communications. With regard to the TI applications, NC has shown an excellent ability for enhancing robustness and performance when used on intermediate nodes in the network and the NC technique assists the network operator in the task of increasing the reliability of its data storage against the failure of caching or computing nodes. Ref. [46] describes the integration of NC and SDN as a possible approach to meet the low-latency requirements of TI.

3.2.5. Serving Gateway (SGW)

This serves the function of routing and forwarding of the surgeon (user) data packets.

3.2.6. Packet Gateway (PGW)

This provides a critical network function for LTE mobile core networks known as the evolved packet core (EPC). It acts as the interface between the 4G (LTE) network and other packet data networks.

3.3. Slave Domain

The slave domain contains a teleoperator, such as a surgical robot, and is directly controlled by the master domain via various command signals that define position and velocity. The slave domain simultaneously receives data and transmits the force signals in the remote environment through kinesthetic force feedback data [47]. In addition to the command and feedback signals, energy is exchanged between the primary(master) and secondary (slave) domains, thereby closing the global control loop. The TI support engines are located at the edge of the network and provide AI and machine learning capabilities that play a key role in the overall functioning of the system. The elements of the secondary domain are as follows:

3.3.1. Robotic Arms

These are the left–right dual telesurgery robotic arms under the supervision of the surgeons or doctors. The surgical robot is equipped with a mechanical arm tactile sensor, and feedback facilitates remote diagnosis and transmission of direct physical movement directly or indirectly.

3.3.2. Haptic Devices

The slave domain surgery robot is equipped with a tactile sensor that displays the feedback signals on the graphical display at the master domain. Both the master and slave domains send and receive real-time data which are displayed on the graphical display.

3.3.3. Full High Definition Camera

This is used to capture the surgeries in the slave domain.

Finally, realizing 5G-enabled tactile internet-based smart hospital telesurgery involves the following functional considerations: latency; reliability; availability; bandwidth; and scalability.

4. Proposed TI-SDOAN System Architecture and Mechanism

This section describes the proposed cloud-based SD-TWDM-PON system architecture that includes a cloudlet, SDN, TWDM-PON, and WLAN. The open-flow-based SD controller is capable of communicating with the northbound application programming interface APIs and transport the services in the southbound APIs. The open flow-based SD controller manages the traffic flows between the optical network unit–access point (ONU-AP) and OLT. To assist the highly low delay, need for TI services in cloudlets, the envisioned cloud-integrated TI-SDOAN network is built on the combination of a cost-effective, simple, and capacity-centric NG-PON2 WLAN, and computation and storage-centric cloudlets. Moreover, cloudlets enhance OANs, where cloudlets are co-located with Wi-Fi access points (AP) that interface with the optical network units (ONUs) of a shared fiber backhaul.

Figure 2 shows the cloudlet-enhanced tactile internet resource allocation TI-SDOAN communication architecture. The optical fiber backhaul has an IEEE 802.3av 10 Gb/s

EPON that extends the optical fiber range to 10–20 km, the distance between the SD-OLT to SD -ONU-AP. The SD-OLT is located at the central office and connected to different ONU-APs (WiFi Mesh network) via tree topology. The remote cloud servers are connected to the SD-OLT via dedicated fiber links. In addition, the cloudlet servers are placed at the optical-wireless network edge and connected to the SD-ONU-AP. This architecture consists of three respective layers such as service layer, transport (control plane) layer and infrastructure layer (data plane), it also consists of two interfaces, i.e., SBAP and NBAPI. With four components: a software-defined controller, a software-defined-OLT (SD-OLT), software-defined-access points (SD-ONU-AP), and a MUX/DEMUX to combine/split the operating signal of one or more wavelengths. The service layer is responsible for providing the different services for the clients. The Transport layer (control plane) is responsible for transmitting and receiving the data packet information from the applications orchestrating the client to the SDN controller. The infrastructure layer (data plane) is where the actual physical transfer of control and data packets takes place [48].

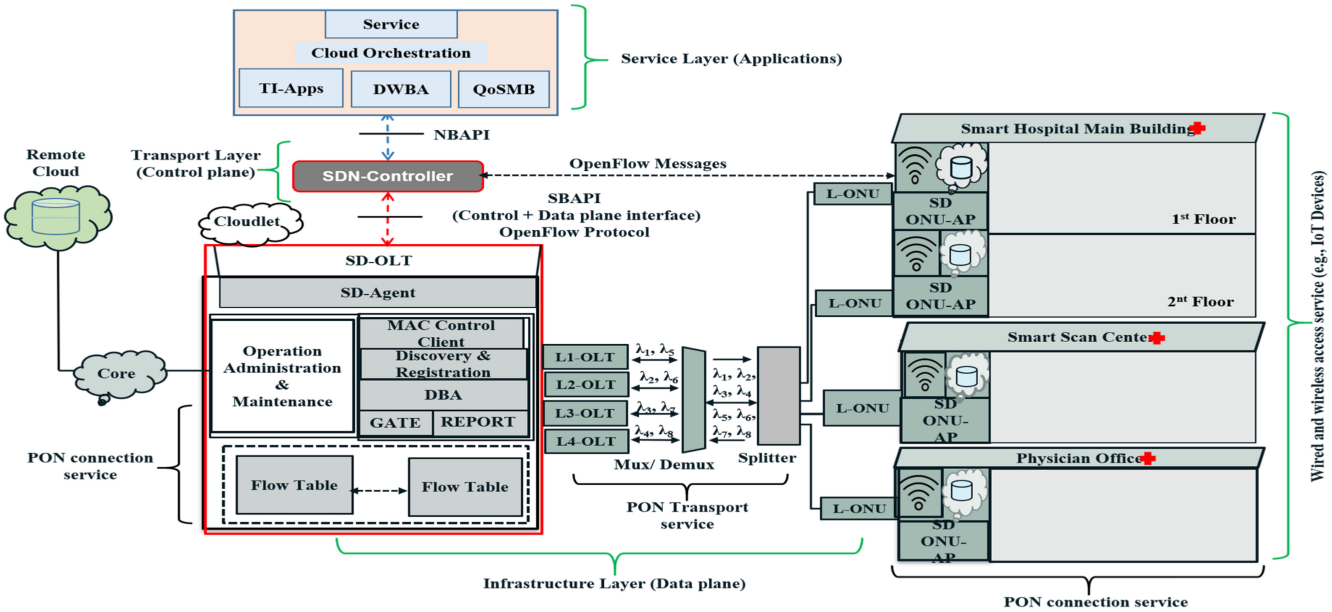


Figure 2. Smart hospital cloudlet-based TI-SDOAN network communication architecture.

The SDOAN-SDN Controller has an interface with the clients (SDN application management, i.e., Tactile Internet-DWBA service) via north-bound API (NB-API). The controller can interface with the SD-OLT through the Southbound API (SB-API). The SDN controller, which connects several SD-OLTs, has the intelligence part of the whole access network and can be run on a dedicated server located in the cloud (data center) or backbone of the access provider, and manages the TI-DWBA schemes. Therefore, to achieve better customer and service-level differentiation, SD-OLT has an SDN control interface with tactile internet applications (services) to dynamically control the resource allocation. Then, the TI data packets are transported from the SDN controller layer to the infrastructure layer via the Open-Flow protocol, which is transported the data to TWDM-PON connection services such as SD-OLT, SD-ONU. TWDM-PON transport services are used to process the functionality of the signal MUX/DEMUX to combine/split the operating signal of one or more wavelengths. The splitter divides the feeder fiber line and amplifies the transmission to provide the necessary power budget to reach the dispersed ONUs. Finally, we propose an enhanced SD-ONU-AP, which retains standard ONU-AP capabilities and also includes an embedded OpenFlow agent and tunable transmitter. An SD-ONU-AP operates in a fully decentralized manner, and it schedules transmissions to assign dynamically allocated upstream bandwidth to the associated wireless end-user devices.

4.1. SD-OLT

The proposed SD-OLT enables centralized control of the SDOAN system and connects the SDOAN system to the larger metro and core area networks. It was designed to support the TWDM-PON protocol, and the SD-OLT consists of four Line-OLTs connected to the power splitter and SD-ONUs. SD-OLT components of Software Defined agent (SD-AGENT), operation administration management (OAM), dynamic bandwidth allocation (DBA), multipoint control protocol (MPCP), and flow table. The SD-Agent is used to communicate with the SDN controller and SD-OLT, and is also used for controlling the traffic flow of packets. The OAM stands for operations, administration, and maintenance, which maintains all the processes, activities, tools, and standards involved with the operation, administration, and maintenance of the networking systems. MPCP works on the MAC layer to perform bandwidth allocation and the following functions: The MPCP controls the auto-discovery process, timeslot/bandwidth assignment to Line-ONU-APs, and the time reference to synchronize Line-ONU-APs. The DBA is controlled by the OLT, which allocates the bandwidth for ONU and receives in the upstream direction and broadcasts only in the downstream direction and uses REPORT and GATE messages to create a transmission schedule for transmitting Line-ONU-AP. A GATE message is used downstream to convey the assigned bandwidth information from SD-OLT to Line-ONU-AP, and REPORT messages are used upstream by the ONU-AP to report its bandwidth request to an SD-OLT [49]. Flow tables consist of flow entries, each of which determines how packets belonging to a flow will be processed and forwarded.

4.2. SD-ONU-AP

Since SD-ONU-APs are decentralized entities in the proposed system architecture as shown in Figure 3, they can be assign bandwidth and schedule transmissions of the associated end devices. The SD-ONU-AP has a tunable transmitter and receivers. The L-ONU-AP consists of an SD-Agent, MPCP, multiple flow table, access points and a user–network interface (UNI). The SD-Agent controls all packets of the ONU-APs and communicates with the SD controller and SD-OLT. The MAC controller contains auto-discovery and registration, a report generator, and GATE processing. In the SD-ONU-AP, we use a multiple flow table that contains standard information about the flow table, the flow table responsible for classifying and separating the packet based on their importance. such as source/destination MAC and IP address, class of service (CoS) and types of service (ToS), transmission control protocol (TCP) and user datagram protocol (UDP) source port. Traffic from a particular TCP/UDP source port, we can categorize the traffic as Tactile Internet (TI), Expedited Forwarding (EF), Assured Forwarding (AF) and Best Effort (BE) traffic. After that, the traffic is maintained by the Queue. The CoS that classifies traffic according to packet types and importance (for example, the packet of the lowest priority CoS encoded in the HP line will be loaded first, during the next cycle (HP) CoS, which will be encapsulated in the LP line). The OpenFlow Agent enables the SD control operations of the Line-ONU-APs that connect the Line-ONU-APs to the controller and communicate via OpenFlow signaling messages. The end-user is connected to the L-ONU-AP through the UNI (AP). An extended WLAN control framework is used by the wireless station to inform SD-ONU-AP of its upstream bandwidth request, and the control frames are used by the SD-ONU-AP to provide bandwidth to the associated end devices during the cycle time. However, in our proposed Line-ONU-AP, we assume that the Line-ONU-AP and wireless access points have seamless integration. The concept of seamless integration has been recently proposed and described in [50]. The Line-ONU-AP can also be used to provide traffic scheduling so that upstream traffic from wireless user devices (UE) can be carried seamlessly on the TWDM-EPON configuration.

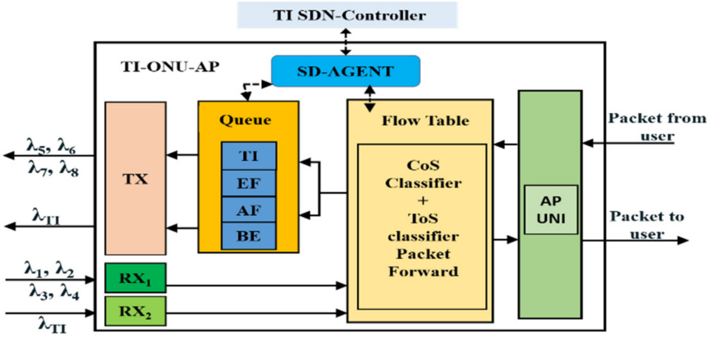


Figure 3. TI-SD-ONU-AP Architecture.

4.3. SD Controller and Its Operations

An SDN controller is an application in SDN that manages the flow control for improved network and application performance. The OpenFlow protocol defines the interface between an SD controller and switch that allows the SDN controller to instruct the switch on how to handle incoming data packets and where to send them. we propose an SD-controlled TI dynamic bandwidth allocation scheme to supervise the wavelength, transmission link-rate, and the management of time to a TI-SDOAN (SD-DWTLRT) in order to reduce the end-to-end delay of the system. The SD-DWTRT operation is shown in Figure 4 and described as follows:

1. By activating the Line-OLT in the SD-OLT, the SD controller begins the registration process with the lowest available transmission link rate.
2. In the Line-OLT, the OAM process begins the discovery method and registers the discovered ONU-AP with the SD controller.
3. The newly registered SD-ONU-AP is added to the database of the SD controller.
4. Based on the initial REPORT messages from the SD-ONU-AP, the DWBA of the SD-OLT assigns the SD-ONU-AP as an initial timeslot.
5. To compensate for changes in the traffic, the SD controller monitors the traffic load of the active Line-OLT and as well as adjusts the transmission link rate or activates/deactivates new Line-OLTs.
6. The SD controller coordinates SD-ONU-APs to use the new changes if there are changes in the transfer rate or if the SD-ONU-APs need to be replaced.

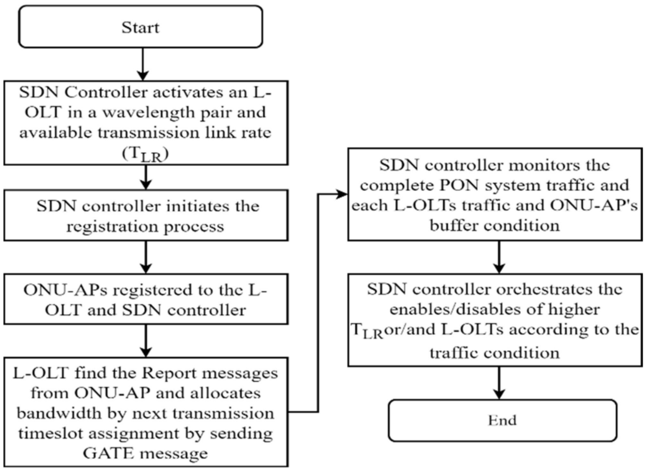


Figure 4. SDN-enabled overall system activation and monitoring.

4.3.1. The Wavelength and Transmission Link-Rate (T_{LR}) Management based on SDN

To manage the wavelength and T_{LR}, the SD controller periodically collects the traffic load from all active Line-OLT and the buffer conditions of each SD-ONU-AP served by a particular Line-OLT. This statistical detail is used as a basis to determine the wavelength and the T_{LR} of the correct configuration and the system is configured for low latency. Hence, this method should be dynamically adjusted via the system provisioning to aid changes in traffic conditions. Therefore, according to the traffic load, the SD controller should calculate the required number of active transceivers TR_{active}:

$$TR_{active} = \frac{\Sigma_{i=1}^{N}\Sigma_{j=1}^{4}\text{ONU\_load}_{ij}}{W_{throughput}} \tag{1}$$

where *ONU-AP_load*, N, j, and $W_{throughput}$ are the requested ONU-AP data, number of registered SD-ONU-APs, number of traffic types acknowledged by the SD-ONU-AP, and highest available throughput with the highest T_{LR}, respectively. After TR_{active} is assigned and the SD controller must determine the T_{LR} to be used on the active L-OLT. Further, we set the threshold transceiver transmission link-rate (TR_{TLR}) is 75% of the system throughput in the low link-rates (1 Gb/s):

$$TR_{tlr} = \begin{cases} TLR_1, & \text{if } BW_{req} < T_{TLR} \\ TLR_2, & \text{if } BW_{req} \geq T_{TLR} \end{cases} \tag{2}$$

where TLR_1, TLR_2, and BW_{req} denotes the 1 Gb/s, 10 Gb/s transmission link-rate (T_{LR}), and requested bandwidth of all ONU-APs on that specific wavelength.

4.3.2. Time Management Mechanism Based on SDN

In the proposed TI-SDOAN architecture, the SD controller conducts the operation of transmission time allocation for every SD-ONU-AP via the DWBA agent inside within the SD-OLT and further, DWBA dynamically allocates the bandwidth to each SD-ONU-AP based on its request. In our proposed SD-TI-DWBA, the SD-OLT initiates the bandwidth allocation computation after collecting all MPCP-REPORT messages from SD-ONU-APs. (Note: Offline DWBA can be upgraded by allocating transmission time to each L-OLT independently). Therefore, this operation is based on the MPCP messages: GATE and REPORT. Then, the SD-OLT implements TI-DWBA, which calculates the bandwidth available ($BW_{available}$) for all ONU-APs and the maximum transmission window ($W_{\max}$) as follows [51,52]:

$$BW_{available} = T_{lr} \times \left(\frac{T^{\substack{Max \\ Cycle}}}{N} - T_{Guard} \right) \times 512 \tag{3}$$

where $T^{\substack{Max \\ Cycle}}$ is the maximum cycle time, T_{Gurad} is the guard time, N is the number of ONU-APs, and 512 bits is the control message length for the proposed system. After that, the DWBA assign the maximum transmission window limit for each ONU-AP:

$$W_{\max} = \left(\frac{BW_{available}}{N} \right) \tag{4}$$

The $W_{\max}$ is distributed for each traffic type and depends on the traffic priority, i.e., Tactile Internet (TI), Expedited Forwarding (EF), Assured Forwarding (AF) and Best Effort (BE), where time is allocated to the highest priority traffic and the remaining lowest priority traffic.

4.3.3. SD Overall Orchestration Management

SD controller manages a database (Flow tables) containing whole details of the SD-OLT and all registered SD-ONU-APs. This database includes the statistical information about the Line-OLTs and the average buffer condition of all SD-ONU-APs. This database is used to eliminate the re-recording process during the wavelength conversion process. Modifications to the wavelength/transmission link-rate configuration are made by the SD controller Sends OFPT_MOD_PROP_OPTICAL signal to SD devices. The media access control client on Line-OLT sends GATE messages to assign transmission time allocation to SD-ONU-APs. Therefore, we proposed combined the MPCP function and the OpenFlow configuration signal flow is shown in Figure 5. The SD controller manages the overall process, and the orchestration reduces the latency of our proposed telesurgery TI-SDOAN system.

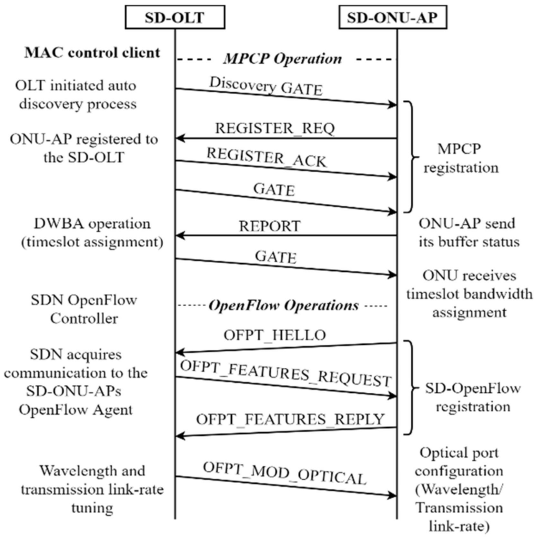
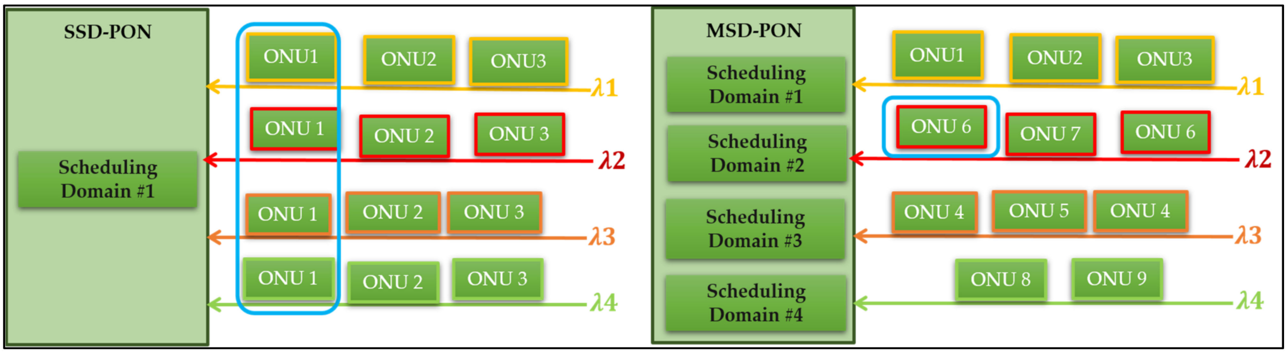


Figure 5. Combined multipoint control protocol (MPCP) and OpenFlow Synchronization.

4.4. TI-DWBA

This section described our proposed software-defined TI-DWBA schemes and supporting the control protocols. These TI-DWBA schemes are implemented in the IEEE EPON offline DWBA and inter-PON scheduling approach based on the non-prediction oriented gated transmission mechanism (MPCP) and dynamic wavelength and bandwidth allocation (limiter service) method. Therefore, our proposed SDOAN-based SDN-enhanced SD-TWDM-PON uses SD-TI-DWBA to efficiently allocate bandwidth to each SD-ONU-AP. In our proposed architecture, the TI-DWBA mechanism is implemented to dynamically allocate the bandwidth over four pairs of wavelengths, regardless of the time windows/slots for upstream data transmission at each L-ONU-AP [53]. TI-DWBA, proposed as the aim of the scheme, highlights an offline scheduling approach, dynamic wavelength and bandwidth allocation; the SD-OLT will first calculate the wavelength and bandwidth allocation after receiving the REPORT messages from all L-ONU-AP. After collecting and extracting all the REPORT messages, the SD-OLT through the SD controller will obtain queues of information of each L-ONU-AP bandwidth requirement which calculates the bandwidth assigned to each ONU and the number of active wavelengths. This information is sent to SD-ONU-APs via a GATE message. The offline-DWBA algorithms improve delay performance at low loads. Inter-PON scheduling is the transport of information from ONU-APs to SD-OLTs, based on the report message contained in the DBA module (inter-ONU scheduling) of sequence occupation information in the SD-OLT. Furthermore, according to [54], there are three main building blocks of the DWBA framework for optical wireless networks: the QoS mapping block (QoSMB), QoS provisioning block (QoSPB), and (QoSB) scheduling block. First, QoSMB is responsible for solving the QoS diversity problem of enabling various technologies on the hybrid network. Second, QoSPB is prompted to determine whether the data packet (connection request) that comes on single or multiple criteria is accommodated (accepted) or dropped (rejected). Third, the SB manages the way data packets are sent or how the data flows from the optical to the wireless domain and vice versa, further categorizing it into different design configurations based on how bandwidth is managed/allocated among multiple wavelengths and the traffic behavior issue: single-scheduling domain (SSD) is similar to TDM-PON, multi-scheduling domain (MSD) is similar to TWDM-PON, and wavelength-agile (WA) is a combination of MSD and SSD-PON architecture is shown in Figure 6 [55]. The MSD domain was chosen because studies have shown that the user's traffic behavior on access networks has different busy times (e.g., TI-traffic and non-TI-traffic). For instance, during the day, some L-ONU-APs can have more bandwidth than others; for instance, an L-SD-ONU-AP that is serving a hospital campus office building will have more traffic compared with those serving other L-SD-ONU-Aps, such as users inside the building. Furthermore, by enabling software defined in the SD-OLT, network operators can change the wavelength and bandwidth allocation for each L-ONU-AP.



(**a**) (**b**)

Figure 6. Illustrations of the passive optical network (PON) solutions (**a**) single-scheduling domain (SSD), (**b**) multi-scheduling domain (MSD).

In our new TI-DWBA algorithm, we have designed an MSD-PON scheduling scheme with QoS support for SDOAN, which is responsible for SD-ONU-AP scheduling a specific upstream channel and time slots. In MSD-PON, SD-OLT provides SD-ONU-AP access to only one wavelength at a time to transmit buffer data. Since an SD-ONU-AP is only allowed to transmit data at one wavelength at a time, multiple SD-ONU-Aps can transmit data at once in different wavelengths, as shown in Figure 6b. The SD-OLT granted time slots to the specific SD-ONU-AP depends on the DWBA algorithm employed by the OLT. It is similar to TWDM-PON. Here, the data traffic is categorized as the TI/non-TI based on the SD-ONU-AP requests and TI transport is given higher priority as TI transport is more sensible. Hence, it is designed to handle traffic allocation as shown in Algorithm 1 to support the traffic with four priority queues at each ONU, namely the tactile internet (TI), expedited forwarding (EF), assured forwarding (AF), and best effort (BE) queues. Four pairs of wavelengths are used, that is, ({λ1, λ5}, {λ2, λ6}, {λ3, λ7}, {λ4, λ8}), where λ1–λ4 indicate downstream wavelengths, and λ5–λ8 indicate upstream wavelengths. When receiving SD-OLT REPORT messages [56], it initially defines the packet and calculates the required times according to each traffic type. TI-DWBA first verifies the available and required timeslot to allocate all requested time locations for TI traffic. TI-DWBA then checks the remaining time locations and allocates time for EF traffic. After allocating EF AF and BE traffic timeslots, TI-DWBA verifies the remaining timeslots and is still available, which allows time for BE traffic. After TI-DWBA calculates time slots for all traffic, SD-OLT sends a GATE message (*start time*, *length*, *and wavelength*) for each traffic of all SD-ONU-AP. Moreover, we also separated the hybrid L-SD-ONU-AP and L-ONU into two groups (Office of Building and inside the hospital floors).

Algorithm 1 Pseudocode for TI-DWBA scheme.

```
$i$ = number of ONUs (64)
$w_{TI}$ = wavelength for TI transmission
$RTTi$ = round-trip time of the $i$ ONU
$Tavailable$ = scheduled time for upstream transmission
$Tguard$ = guard band interval
$maxLength$ = maximum transmission timeslot of ONUi
$Report.j.length$ = j packets (bits) at the ONU$_i$ buffer
$Bleft$ = remaining bandwidth
For every wavelength, $w$, where $w \in \{1, \ldots ,4\}$ do {
  For every received $Report.j.length$ of ONU$_k$, where $k \in \{i/w\}$, $j \in \{TI, EF, AF, BE\}$ do {
    $startTime = Tavailable + Tguard$
    if j = TI then {
      if $Report.j.length > maxLength$ then {
        $Report.j.length = maxLength$
        GRANT = {$startTime$-$RTTi$, $maxLength$, $w_{TI}$}
        Send GRANT message
      } else {
        GRANT = {$startTime$-$RTTi$, $Report.j.length$, $w_{TI}$}
        Send GRANT message
      }
    } else {
      if $Report.j.length > maxLength$ then {
        $Report.j.length = maxLength$
        GRANT = {$startTime$-$RTTi$, $maxLength$, $w$}
        Send GRANT message
      }else {
        GRANT = {$startTime$-$RTTi$, $Report.j.length$, $w$}
        Send GRANT message
      }
    }
    $Bleft = maxLength$–$Report.j.length$
    $maxLength = Bleft$
    $Tavalaible = startTime + Report.j.length$
  }
}
```

4.5. TI-SDOAN QoS Support

As illustrated in Figure 2, SDOAN can deliver our classes of services, namely TI, EF, AF and BE. To support these services via TI-SDOAN, traffic classification and CoS mapping based on traffic type, characteristics and QoS requirements are conducted at SD-ONU-AP, as shown in Table 3 [2,44,57]. Here, owing to their stringent requirements, TI services are devoted to a CoS with high priority. The Constant bit rate (CPR) is a CoS that focuses primarily on EF traffic and cannot be used to meet their stringent requirements for TI services.

Table 3. QoS Requirements and class of service (CoS) Mapping in TI-SDOAN.

Service Type	Applications	Quality of Service		
		Data Rate	**End-To-End Delay (One-Way)**	**CoS Priority**
(TI)	Telesurgery Virtual Reality	10–100 mb/s	$\leq$0.5 ms	1
(EF)	Voice Over IP Audio conferencing	4–128 kb/s	100–150 ms	2
(AF)	Video Streaming Video Conferencing	20 kb/s–6 mb/s	150–250 ms	3
(BE)	Web browsing	Minimum Throughput		4

5. Performance Evaluation

In this section, we validate the effectiveness of the proposed solutions, we build a simulator that models TI-SDOAN using OPNET. We analyze the proposed scheme in terms of system throughput, means packet delay, dropping, and jitter. We have one SD-OLT with 64 SD-ONU-APs, and the downstream and upstream capacity for this SD-OLT is 4 Gbps. The distance between the SD-OLT and SD-ONU-APs is 10–20 km, and each ONU has a finite buffer size of 10 MB. The traffic models AF and BE network models are chosen for their self-similarity and long-range dependence (LRD), whereas the CBR (i.e., EF traffic) uses Poisson distribution. Self-similarity and long-range dependence are utilized to generate the high burst BE and AF traffic with a Hurst Parameter of 0.7, and the packet sizes of AF and BE are Pareto distributed between 512 and 1518 bytes, while TI packet sizes are Pareto distributed at 64 and 1518 bytes., and the EF packet size is constantly distributed with 560 bytes. The maximum cycle times are 1.0 ms and 1.5 ms and the guard time is 1 µs. The simulation parameters are listed in Table 4, and the traffic scenarios are shown in Table 5. In order to show the performance of the proposed SDOAN, architecture EF traffic accounts for 10% of the total access traffic. However, the remaining 90% traffic is distributed as follows: To test the strength of our resource allocation scheme in meeting TI traffic delay requirements for different arrival rates, we differentiate the percentage of TI traffic between 24%, 30% and 36%. Then, the AF (Video) traffic packet arrival rates are 16%, 20% and 24% and BE (Data) traffic packet arrival rates are 50%, 40% and 30%. We simulated three scenarios for TI-DWBA: S1, S2 and S3. These three notable scenarios with different TI service, EF service, AF service and BE service ratios are designed and analyzed to show the performance of high priority traffic management.

Table 4. Simulation parameters.

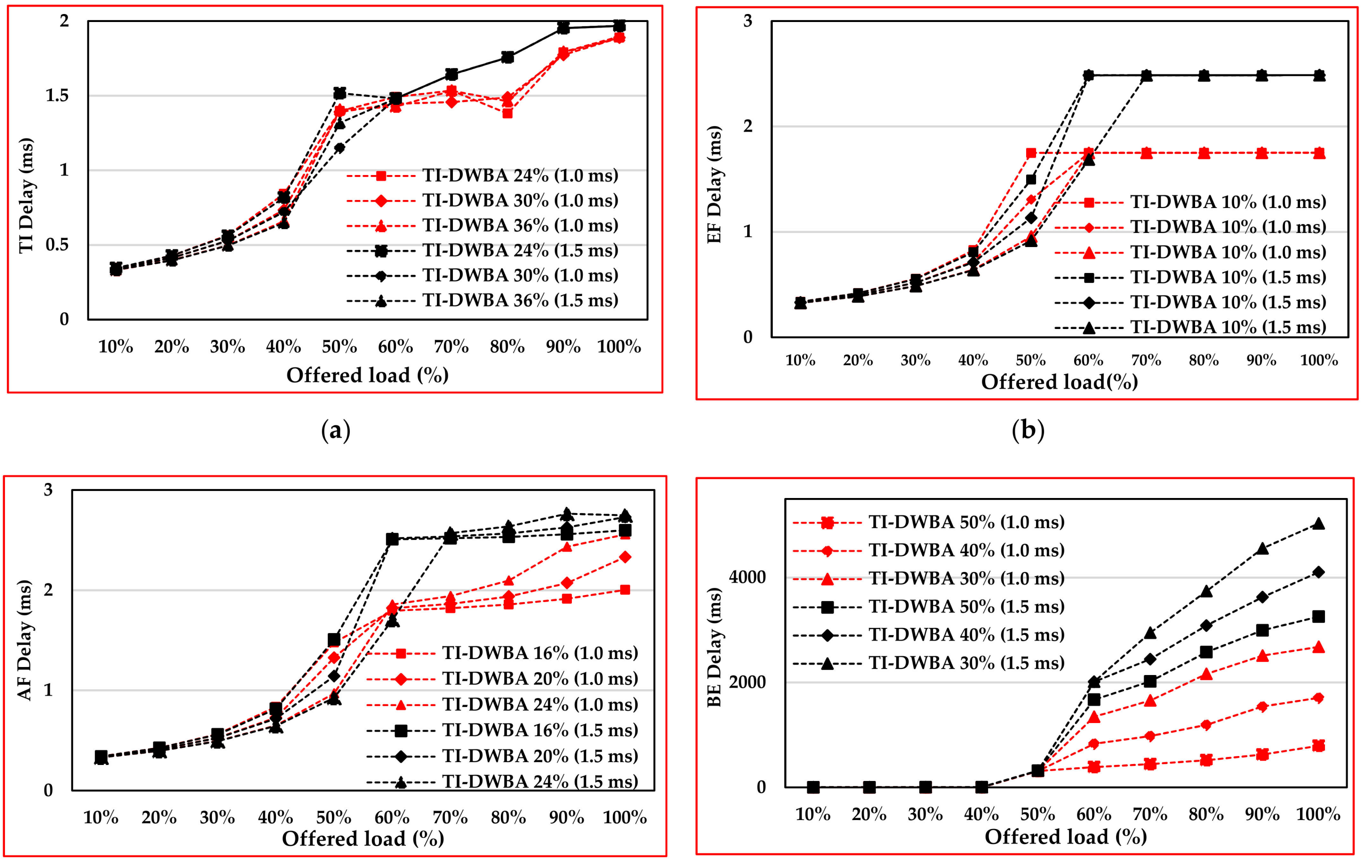
Parameter	Value
Number of SD-OLT	1
Number of SD-ONU-AP	64
Number of Wavelengths	4
Up/Down link capacity	4 Gbps
OLT-ONU distance	10–20 km
Max cycle time	1.0 ms, 1.5 ms
Guard time	1 µs
Tuning time	100 ns
DWBA Computation	10 µs
Control message length (bytes)	64
ONU buffer size	10 Mb
Non-TI packet size (bytes)	(64, 1518)
Non-TI (EF) packet size (bytes)	Constant (70)
TI packet Size (bytes)	(64, 1518)
Traffic distribution	Pareto

Table 5. TI-DWBA traffic profile.

Class of Service (CoS)	Scenario 1	Scenario 2	Scenario 3
TI (Tactile Internet)	24%	30%	36%
EF (Voice)	10%	10%	10%
AF(Video)	16%	20%	24%
BE (Data)	50%	40%	30%

5.1. Mean Packet Delay

Mean packet delay occurs when the packets arrive at the SD-ONU-AP at random times. Each packet must wait for the appropriate time slot to be transmitted in the upstream direction. This waiting time is referred to as the packet delay, which consists of polling delay, granting delay, and queuing delay. Figure 7 shows the improvement of delays in the different scenarios. The TI, EF, AF, and BE traffic delays of the proposed TI-DWBA increased or decreased depending on the number of SD-ONUs sharing the same wavelength. The packet delays with the TI redirect ratio for TI, EF, AF, and BE as well as the overall packet delays were shorter. When the traffic load was more than 70%, the TI, EF, AF, and BE delays of the proposed mechanism were of the same value because, under higher traffic loads, SD-OLT is required to activate all available wavelengths to maintain system performance. When the traffic load was 60% to 90%, the scenario with a high ratio of TI had the greatest improvement in the packet delay for each packet. The EF and AF delays are still less than 2 ms and 2.5 ms, respectively. Additionally, for longer transmission cycle times, delays have increased as SD-ONU-APs have to wait longer until designated transmission slots arrive. However, our proposed TI-traffic is archived less delayed can be seen in Figure 7a, that TI traffic achieve the lowest delay because the TI has the highest priority level compared with the other traffic types, thus meet the requirements of TI delay constraint.



(**a**) (**b**)

(**c**) (**d**)

Figure 7. Mean packet delay comparison in different scenarios in (**a**) TI Delay, (**b**) EF Delay, (**c**) AF Delay, (**d**) BE Delay, 1.0 and 1.5 (ms) cycle time.

5.2. TI Jitter

Delay variance or jitter is the packet transfer delay variation, and it has a significant impact on voice quality. A smaller jitter value is required to deliver a better and high-quality voice signal. The TI delay variance TI jitter, can be calculated as $\sigma^2 = \Sigma_{i=1}^{N}\left(d_i^{TI} - d\right)^2/N$, where d_i^{TI} represents the delay time of the TI packet, d denotes the average delay time of the TI traffic, and N denotes the total number of received TI packets. Figure 8 shows the TI Jitter for two different cycle times. The TI jitter performance in Scenarios 2 and 3 for 1.5 ms cycle time with a traffic load of 90% to 100% suddenly increased because the AF traffic was higher than in the other scenarios. This causes the remaining traffic to be sent in the next given cycle time. Further, at a 1.5 ms rotation time, the timeslot provided by SD-OLT is sufficient to send AF traffic to SD-ONU-APs, and the same goes for the rest of the traffic, such as EF and BE traffic.

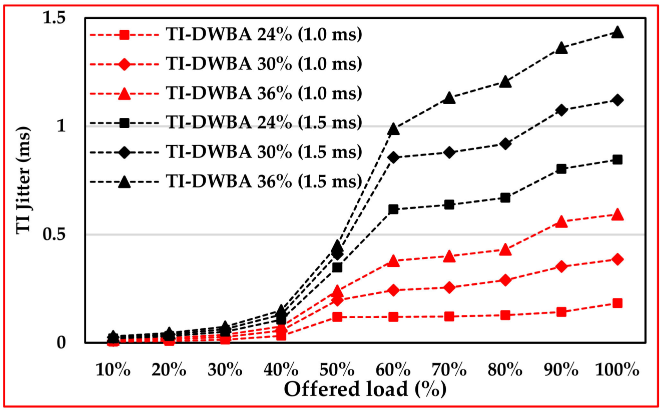


Figure 8. TI Jitter 1.0 (ms) and 1.5 (ms) cycle time.

5.3. System Throughput

System throughput is defined as the sum of the data rates transmitted to all terminal ports in the network in network SD-ONU-APs. Therefore, in our proposed architecture, the system throughput is the sum of all the throughputs for all communication that occurs between the SD-OLT and SD-ONU-APs and the users. Figure 9 shows the system throughput in different scenarios for different traffic loads. The system performance is the PON link-rate, which is multiplied by the combined performance, which includes management and integration overlays. The proposed TI-DWBA had lower performance when the maximum rotation times were between 1.0 and 1.5 ms, when the supplied load was less than 50%. As the number of requests handled increases with an increase in TI traffic, the system throughput increases. Furthermore, the system throughput increases as the share of TI traffic is increased.

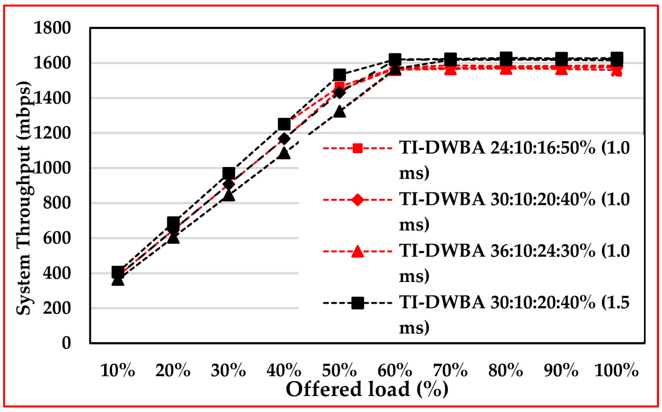


Figure 9. Overall system throughput in cycle time 1.0 (ms) and 1.5 (ms).

5.4. Packet Loss

Packet loss or dropping depends on the cycle time and buffer size. When a cycle is higher, there will be less packet drop because the SD-ONU-APs will have more time slots to send its queues. However, the larger cycle time will also result in a higher packet delay and no packet loss for the higher-priority packets. Regarding buffer sizes, increasing the buffer size results in less packet loss but increases the queue delay. Figure 10 shows the BE drop versus the traffic load for different scenarios. The simulation results show that the BE packet drop of the TI-DWBA was 0 (zero) when the traffic load was below 40%. However, to manage the required QoS performance in high traffic conditions, the lower-priority BE packets will be dropped if the buffer is full. Furthermore, the scenarios with a 1.0 ms cycle time had lower packet loss ratios, 1.5 had more transmission time because on each cycle the total transmission time is 1.5 ms vs. 1 ms. Hence, in each cycle, the lowest priority packets would have to wait longer than 1 ms. Therefore, as seen in Figure 10, the 1.5 ms cycle time has more packet drop compared with 1 ms at the higher traffic loads, the BE packet losses of TI-DWBA were the same at all traffic scenarios and at all cycle times, indicating that the proposed system configuration does not affect the packet loss.

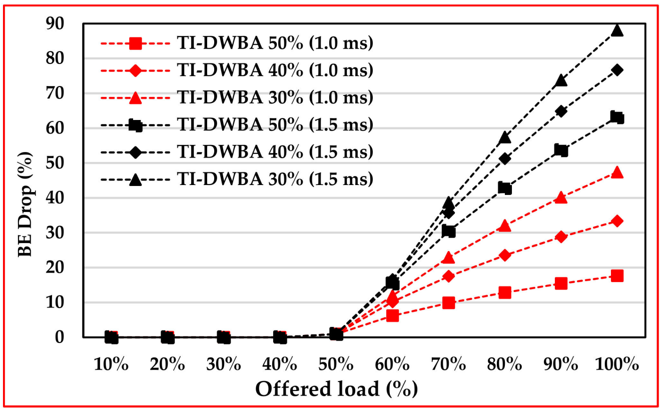


Figure 10. BE packet drop in cycle time 1.0 (ms) and 1.5 (ms).

6. Conclusions

In this paper, we first provided insights into details about the future of low-latency telesurgery systems for smart healthcare in the 5G era. Then, we elaborated on the existing communication infrastructure to support future delay-sensitive tactile Internet applications and regular high-bandwidth applications. Next, we proposed a cloudlet and SDN-enhanced NG-PON2-based TI-SDOAN system communication architecture and implemented a new TI-DWBA to support the bandwidth-intensive healthcare traffic and delay-sensitive H2M transport. TI resource provision scheme for TWDM-PONs, where an SD controller plans dynamic resource allocation to manage transmission between monitoring the active wavelengths, link rates, time management and QoS performance. The SD controller monitors the global traffic conditions and activates the process enough OLT transceivers and maintain the QoS requirements. The most important aspect of these techniques is the priority implementation of the CoS queues while facilitating and enhancing the performance of the critical design parameters of the TI-DWBA algorithms for supporting TI and non-TI traffic under different traffic loads. To solve the problem of efficient upstream bandwidth management in TWDM-PONs, different ONU scheduling mechanisms are discussed and are proposed to efficiently arbitrate the QoS-based TI-DWBA channel bandwidth for MSD-PON on TWDM-PON. Our simulation results revealed the superiority of the proposed mechanism for protecting the QoS under multiple scenarios. The simulation results have been analyzed and showed that our proposed TI-DWBA algorithm performed better at 1.0 and 1.5 ms cycle times and Figure 7a shows the TI delay is reduced compared to the non-TI delays. Finally, the simulation results demonstrated that the proposed architecture and its operations are capable of managing the SDOAN resource provision scheme to meet the QoS requirements. Furthermore, the simulation results showed that the proposed mechanism could maintain the overall system performance. Furthermore, the SDN-based passive optical cloud data center is proposed to improve the QoS/QoE requirements for future work.

Author Contributions: Conceptualization, implementation-writing, E.G.; Result analysis-review-editing, A.T.L. and M.S.A.-R.; Supervision and funding, I.-S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded by the Ministry of Science and Technology (MOST): 108-2221-E-155-012, Taiwan.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are thankful to the anonymous reviewers for their constructive and logical comments.

Conflicts of Interest: The authors declare no conflict of interest.

Abbrevitions

Notations	Description
IIoT	Industrail Internet of Things
5G	Fifth Generation Network
TI	Tactile Internet
SDN	Software Defined Network
OAN	Optical Access Network
SDOAN	Software Defined Optical Access Network
DBA	Dynamic Bandwidth Allocation
DWBA	Dynamic Wavelength and Bandwidth Allocation
QoS	Quality of Service
PON	Passive Optical Network
NG-PON2	Next Generation Passive Optical Networks 2
TWDM	Time and Wavelength Division Multiplexing
ODN	Optical Distribution Network
NBAPI	NorthBound Application Programming Interface
SBAPI	SouthBound Application Programming Interface
SD-OLT	Software-Defined-Optical Line Terminal
SD-ONU-AP	Softwate Defined-Optical Network Unit-Access Point
L-ONU	Line-Optical Network Uunit
VR/AR	Virutual/Augumented Reality
T_{LR}	Transmission Link-Rate
EF	Expedited Forwarding (Voice)
AF	Assured Forwarding (Video)
BE	Best Effort
CoS	Class of Service
ToS	Type of Service
QoE	Quality of experience
CBR	Constant Bit Rate
M2M	Machie-To-Machine Communication
H2M	Human-To-Machine Communication

References

1. Fettweis, G.P. The Tactile Internet: Applications and Challenges. *IEEE Veh. Technol. Mag.* **2014**, *9*, 64–70. [CrossRef]
2. Holland, O.; Steinbach, E.; Prasad, R.V.; Liu, Q.; Dawy, V. The IEEE 1918.1 Tactile Internet' standards working group and its standards. *Proc. IEEE* **2019**, *107*, 256–279. [CrossRef]
3. Ganesan, E.; Hwang, I.-S.; Liem, A.T. Resource Allocation for Tactile Internet via Software-Defined FiWi Access Network. In Proceedings of the 2020 International Computer Symposium (ICS), Tainan, Taiwan, 17–19 December 2020; pp. 283–287.
4. Simsek, M.; Aijaz, A.; Dohler, M.; Sachs, J.; Fettweis, G. 5G-Enabled Tactile Internet. *IEEE J. Sel. Areas Commun.* **2016**, *34*, 460–473. [CrossRef]
5. Wei, X.; Duan, Q.; Zhou, L. A QoE-driven tactile internet architecture for smart city. *IEEE Netw.* **2020**, *334*, 130–136. [CrossRef]
6. Sachs, J.; Andersson, L.A.A.; Araujo, J.; Curescu, C.; Lundsjo, J.; Rune, G.; Steinbach, E.; Wikstrom, G. Adaptive 5G Low-Latency Communication for Tactile InternEt Services. *Proc. IEEE* **2018**, *107*, 325–349. [CrossRef]
7. Maier, M.; Chowdhury, M.; Rimal, B.P.; Van, D.P. The tactile internet: Vision, recent progress, and open challenges. *IEEE Commun. Mag.* **2016**, *54*, 138–145. [CrossRef]

8. Antonkoglou, A.; Xu, X.; Steinbach, E.; Mahmoodi, T.; Dohler, M. Towards haptic communication over the 5G tactile internet. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 3034–3059. [CrossRef]
9. Wong, E.; Dias, M.P.I.; Ruan, L. Predictive Resource Allocation for Tactile Internet Capable Passive Optical LANs. *J. Light. Technol.* **2017**, *35*, 2629–2641. [CrossRef]
10. Steinbach, E.; Hirche, S.; Ernst, M.; Brandi, F.; Chaudhari, R.; Kammerl, J.; Vittorias, I. Haptic Communications. *Proc. IEEE* **2012**, *100*, 937–956. [CrossRef]
11. Steinbach, E.; Strese, M.; Eid, M.; Liu, X.; Bhardwaj, A.; Liu, Q.; Al-Ja'Afreh, M.; Mahmoodi, T.; Hassen, R.; El Saddik, A.; et al. Haptic Codecs for the Tactile Internet. *Proc. IEEE* **2018**, *107*, 447–470. [CrossRef]
12. Liu, Y.; Yang, Y.; Han, P.; Shao, Z.; Li, C. Virtual Network Embedding in Fiber-Wireless Access Networks for Resource-Efficient IoT Service Provisioning. *IEEE Access* **2019**, *7*, 65506–65517. [CrossRef]
13. IEEE P802.3av 10G-Ethernet Passive Optical Network Task Force. Available online: http://www.ieee802.org/3/av/index.html (accessed on 10 February 2021).
14. Nesset, D. NG-PON2 Technology and Standards. *J. Light. Technol.* **2015**, *33*, 1136–1143. [CrossRef]
15. Kim, K.; Doo, K.H.; Lee, H.H.; Kim, S.H.; Park, H.; Yeol oh, J.; Chung, H.S. High speed and low latency passive optical net-work for 5G wireless systems. *J. Light. Technol.* **2019**, *37*, 2873–2882. [CrossRef]
16. 40-Gigabit-Capable Passive Optical Networks 2 (NG-PON2), Document ITU-T G.989 Series Recommendations. October 2015. Available online: http://www.itu.int/rec/T-REC-G.989.1-201303-I/en. (accessed on 10 February 2021).
17. IEEE P802.3ca 100G-EPON Task Force. Available online: http://www.ieee802.org/3/ca/ (accessed on 10 February 2021).
18. Nakayama, Y.; Uzawa, H.; Hisano, D.; Ujikawa, H.; Nakamura, H.; Terada, J.; Otaka, A. Efficient DWBA Algorithm for TWDM-PON with Mobile Fronthaul in 5G Networks. *IEEE Glob. Commun. Conf.* **2017**, 1–6. [CrossRef]
19. Valkanis, A.; Nicopolitidis, P.; Papadimitriou, G.; Kallergis, D.; Douligeris, C.; Bamidis, P.D. Efficient Resource Allocation in Tactile-Capable Ethernet Passive Optical Healthcare LANs. *IEEE Access* **2020**, *8*, 52981–52995. [CrossRef]
20. Orphanoudakis, T.; Kosmatos, E.; Angelopoulos, J.; Stavdas, A. Exploiting PONs for mobile backhaul. *IEEE Commun. Mag.* **2013**, *51*, S27–S34. [CrossRef]
21. Maier, M.; Ebrahimzada, A. Towards Immersive tactile internet experiences: Low-latency FiWi enhanced mobile networks with edge intelligence. *J. Opt. Commun. Netw.* **2019**, *11*, B10–B25. [CrossRef]
22. Fiorani, M.; Skubic, B.; Marensson, J.; Lalcarenghi, L.; Castoldi, P.; Wosinka, L.; Monti, P. On the design of 5G transport networks. *Photonic Netw. Commun.* **2015**, *30*, 403–415. [CrossRef]
23. Cvijietic, N. SDN for optical access networks. *Adv. Photonic Commun. OSA Paper PM3C.4* **2014**, 1–2. [CrossRef]
24. Kreutz, D.; Ramos, F.M.V.; Verissimo, P.E.; Rothenberg, C.E.; Azodolmolky, S.; Uhlig, S. Software-Defined Networking: A Comprehensive Survey. *Proc. IEEE* **2015**, *103*, 14–76. [CrossRef]
25. Huwaei's Smart Hospital Solutions. Available online: https://rendta.com/wp-content/uploads/2015/09/Huawei-Smart-Hospital-Solutions-Brochure-HD.pdf (accessed on 20 February 2021).
26. Li, C.; Guo, W.; Wang, W.; Hu, W.; Xia, M. Programmable bandwidth management in software-defined EPON architecture. *Opt. Commun.* **2016**, *370*, 43–48. [CrossRef]
27. Hwang, I.S.; Tesi, C.; Pakphan, A.F.; Ab-Rahman, M.S.; Liem, A.T.; Rianto, A. Software-defined time-shifted IPTV architec-ture for locality-awareness TWDM-PON. *Optics* **2020**, *207*, 1–9.
28. Kondepu, K.; Valcarenghi, L.; Van, D.P.; Castoldi, P. Trading Energy Savings and Network Performance in Reconfigurable TWDM-PONs. *J. Opt. Commun. Netw.* **2015**, *7*, 470–479. [CrossRef]
29. Hwang, I.S.; Yeh, T.J.; Hwang, B.J.; Lee, J.Y. Synchronous interleaved dynamic bandwidth assignment for quality of service over GPON-LTE converged network. *J. Int. Technol.* **2015**, *16*, 1259–1270.
30. Mohammadani, K.; Butt, R.A.; Memon, K.A.; Hassan, F.; Majeed, A.; Kumar, R. Highest Cost First-Based QoS Mapping Scheme for Fiber Wireless Architecture. *Photonics* **2020**, *7*, 114. [CrossRef]
31. Muciaccia, T.; Gargano, F.; Passaro, V.M.N. Passive Optical Access Networks: State of the Art and Future Evolution. *Photonics* **2014**, *1*, 323–346. [CrossRef]
32. Thyagaturu, A.S.; Mercian, A.; McGarry, M.P.; Reisslein, M.; Kellerer, W. Software Defined Optical Networks (SDONs): A Comprehensive Survey. *IEEE Commun. Surv. Tutor.* **2016**, *18*, 2738–2786. [CrossRef]
33. Marotta, A.; Cassioli, D.; Kondepu, K.; Antonelli, C.; Valcarenghi, L. Exploiting flexible functional split in converged software defined access networks. *J. Opt. Commun. Netw.* **2019**, *11*, 536–546. [CrossRef]
34. Yang, H.; Zhang, J.; Zhao, Y.; Han, J.; Lin, Y.; Lee, Y. SUdoi:Software defined networking for ubiquitous data center optical interconnection. *IEEE Commun. Mag.* **2016**, *54*, 86–95. [CrossRef]
35. Sedaghat, S.; Jahangir, A.H. RT-TelSurg: Real Time Telesurgery Using SDN, Fog, and Cloud as Infrastructures. *IEEE Access* **2021**, *9*, 52238–52251. [CrossRef]
36. Gupta, R.; Tanwar, S.; Tyagi, S.; Kumar, N. Tactile-Internet-Based Telesurgery System for Healthcare 4.0: An Architecture, Research Challenges, and Future Directions. *IEEE Netw.* **2019**, *33*, 22–29. [CrossRef]
37. Miao, Y.; Jiang, Y.; Peng, L.; Hossain, M.S.; Muhammad, G. Telesurgery Robot Based on 5G Tactile Internet. *Mob. Netw. Appl.* **2018**, *23*, 1645–1654. [CrossRef]
38. Mukherjee, M.; Guo, M.; Lloret, J.; Zhang, Q. Leveraging Intelligent Computation Offloading with Fog/Edge Computing for Tactile Internet: Advantages and Limitations. *IEEE Netw.* **2020**, *34*, 322–329. [CrossRef]

39. Madhani, A.; Niemeyer, G.; Salisbury, J. The Black Falcon: A teleoperated surgical instrument for minimally invasive surgery. In Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems. Innovations in Theory Practice and Applications (Cat. No.98CH36190), Victoria, BC, Canada, 17 October 1998; pp. 936–944.
40. Hassan, T.; Hameed, A.; Nisar, S.; Kamal, N.; Hasan, O. Al-Zahrawi: A Telesurgical Robotic System for Minimal Invasive Surgery. *IEEE Syst. J.* **2014**, *10*, 1035–1045. [CrossRef]
41. Subramaniam, S.; Kondepu, K.; Marotta, A. Cross-Layer Design. In *Springer Handbook of Optical Networks*; Springer: Cham, Switzerland, 2020.
42. Leveque, L.; Zhang, W.; Cavaro-Menard, C.; Le Callet, P.; Liu, H. Study of Video Quality Assessment for Telesurgery. *IEEE Access* **2017**, *5*, 9990–9999. [CrossRef]
43. Quek, Z.F.; Provancher, W.R.; Okamura, A.M. Eavaluation of skin deformation tactile feedback for teleoperated surgical tasks. *IEEE. Trans. Hap.* **2019**, *12*, 102–113. [CrossRef]
44. Zhang, Q.; Liu, J.; Zhao, G. Towards 5G enabled tactile robotic telesurgery. *arXiv* **2018**, arXiv:1803.03586.
45. Arslan, M.Y.; Sundaresan, K.; Rangarajan, S. Software-defined networking in cellular radio access networks: Potential and challenges. *IEEE Commun. Mag.* **2015**, *53*, 150–156. [CrossRef]
46. Szabo, D.; Gulyas, A.; Fitzek, F.H.P.; Lucani, D.E. Towards the tactile internet: Decreasing communication latency with net-work coding and software defined networking. In Proceedings of the European Wireless 2015 21th European Wireless Conference, Budapest, Hungary, 20–22 May 2015; pp. 428–433.
47. Aijaz, A.; Dohler, M.; Aghvami, A.H.; Friderikos, V.; Frodigh, M. Realizing the Tactile Internet: Haptic Communications over Next Generation 5G Cellular Networks. *IEEE Wirel. Commun.* **2017**, *24*, 82–89. [CrossRef]
48. Chitimalla, D.; Thota, S.; Savas, S.S.; Tornatore, M.; Lee, S.S.; Lee, H.H.; Park, S.; Chung, H.S.; Mukherjee, B. Application-aware software defined EPON access network. *Photonic Netw. Commun.* **2015**, *30*, 324–336. [CrossRef]
49. Available online: Http://www.ieee1904.org/revision/meeting_archive/2015/10/rmtf_1510_kramer_multicast_outline_1.pdf (accessed on 22 February 2021).
50. Rimal, B.P.; Maier, M.; Satyanarayanan, M. Experimental Testbed for Edge Computing in Fiber-Wireless Broadband Access Networks. *IEEE Commun. Mag.* **2018**, *56*, 160–167. [CrossRef]
51. Hwang, I.S.; Lee, J.Y.; Lai, K.R.; Liem, A.T. Generic QoS-Aware Interleaved dynamic bandwidth allocation in scalable EPONs. *J. Opt. Commun. Netw.* **2012**, *4*, 99–107. [CrossRef]
52. Pakpahan, A.F.; Hwang, I.-S.; Nikoukar, A. OLT Energy Savings via Software-Defined Dynamic Resource Provisioning in TWDM-PONs. *J. Opt. Commun. Netw.* **2017**, *9*, 1019–1029. [CrossRef]
53. Nakayama, Y.; Hisano, D. Wavelength and Bandwidth Allocation for Mobile Fronthaul in TWDM-PON. *IEEE Trans. Commun.* **2019**, *67*, 7642–7655. [CrossRef]
54. Sarigiannidis, A.G.; Iloridou, M.; Nicopolitidis, P.; Papadimitriou, G.; Pavlidou, F.-N.; Sarigiannidis, P.G.; Louta, M.D.; Vitsas, V. Architectures and Bandwidth Allocation Schemes for Hybrid Wireless-Optical Networks. *IEEE Commun. Surv. Tutor.* **2014**, *17*, 427–468. [CrossRef]
55. Rafiq, A.; Hayat, M.F. QoS-Based DWBA Algorithm for NG-EPON. *Electronics* **2019**, *8*, 230. [CrossRef]
56. Liem, A.T.; Hwang, I.S.; Nikoukar, A.A.; Pakphan, A.F. SD-enabled mobile fronthaul dynamic bandwidth and wavelength allocation (DWBA) mechanism in converged TWDM-EPON architecture. In Proceedings of the 2018 6th International Conference on Cyber and IT Service Management (CITSM), Parapat, Indonesia, 7–9 August 2018; pp. 1–6.
57. Neaime, J.; Dhaini, A.R. Resource Management in Cloud and Tactile-Capable Next-Generation Optical Access Networks. *J. Opt. Commun. Netw.* **2018**, *10*, 902–914. [CrossRef]