Abstract—This paper focuses on Service Level Agreement (SLA) based end-to-end Quality of Service (QoS) maintenance across a wireless optical integrated network. We use long term evolution/5G based spectrum access system (SAS) in the wireless network and the optical network is comprised of an Ethernet Passive Optical Network (EPON). The proposal targets a learning-based intelligent SAS where opportunistic allocation of any available bandwidth is done after meeting the SLA requirements. Such an opportunistic allocation is particularly beneficial for nomadic users with varying QoS requirements. The opportunistic allocation is carried out with the help of Vickrey-Clarke-Groves (VCG) auction. The proposal allows the users of the integrated network to decide the payment they want to make in order to opportunistically avail bandwidth. Learning automata is used for the users to intelligently converge to the optimal payment value based on the network load. The payment made by the users is later used by the optical network units of the EPON to prepare the bids for the auction. The proposal has been verified through extensive simulations.

Index Terms—EPON, LTE, service level agreement, VCG auction, learning automata, wireless optical integrated networks.

I. INTRODUCTION

THE last decade has witnessed an exponential increase in the wireless spectrum demands due to the wide-spread usage of hand-held networking devices. Unfortunately, the available wireless spectrum is limited and the proposed mitigation scheme towards shifting to the higher frequency bands (typically 10 GHz and above) results in high signal attenuation [1]. Hence, a dynamic spectrum access (DSA) technique like the three-tier spectrum sharing model known as the spectrum access system (SAS) is suggested to be an effective method to maximize the spectrum utilization [2]. The SAS targets spectrum sharing in the 3.5 GHz citizens broadband radio service (CBRS) band [2], [3].

The SAS maintains a geo-location database with well-defined exclusion zones and manages spectrum sharing in a way that the incumbent operations are guaranteed interference protection according to the terms of their assignments whenever they are present in deployed areas [3]. The incumbents are the high priority CBRS users, and they comprise the highest tier. The secondary users are further classified into two tiers; called second tier priority access license (PAL) users and the lower tier general authorized access (GAA) opportunistic users [1]. The PAL users, which are the direct subscribers of the mobile network operators (MNOs), are protected from the GAA users whereas the GAA users do not get any interference protection guarantees. The GAA users need to be actively managed to provide interference protection to the PAL users [1]. Please note that, we only concentrate on the spectrum sharing between PAL and GAA users by assuming that the incumbents are already protected. The interference mitigation for PAL users must be achieved through sharing of minimum information between the GAA and PAL users as the cellular operators might be reluctant in sharing detailed system information. Further, a large complex system relying on real-time information for interference mitigation may malfunction even with slight delay of reception of a vital information [4].

The GAA users do not have any well-defined agreements and hence, they are essentially nomadic users (e.g., international roaming users). In networking, a nomadic user does not require a long-term service level agreement (SLA) like the incumbents or the PAL users.

In the available literature of SAS, the GAA users are mostly considered as cognitive users where it requires interference management techniques in the physical layer [4]. However, this can be easily avoided if we associate GAA users with the PAL base station (BS) (see Fig. 1) and assume that the MNO perform scheduling of the GAA users on a competitive pay-as-you-go basis. Here, the PAL BS keeps the provision of scheduling on-demand traffic from GAA users on short term basis. This will also ensure that the GAA users do not interfere with the PAL users.

Therefore, a highly flexible SAS is required to efficiently manage the GAA users. Hence, we move on to propose an advanced version of SAS that is managed from the medium access control (MAC) layer. The proposal governs the network operation using an intelligent opportunistic spectrum sharing scheme. The proposal is software controlled and therefore, can be implemented without the requirement of any specialized hardware. Hence, the overall cost of the network is also reduced. In our proposal, we introduce an artificial intelligence (AI) enabled software defined network (SDN) controller that utilizes learning automata (LA) [7] for resource scheduling among PAL and GAA users to achieve net-
work efficiency while satisfying quality of service (QoS) demands [5], [6].

After employing SAS as a wireless interface, the network operators need to overcome the issue of routing the huge incoming traffic from the wireless network to the network core. An optical backhaul might serve the purpose [8]. Thus, we get a wireless optical integrated network (WOIN) illustrated in Fig. 1, where an optical access network is used as the backhaul and a wireless network technology provides the final connectivity [9], [10]. WOINs utilize the data carrying potential of the optical networks and the ubiquity of the wireless networks. The primary choice for the optical part of the network is Ethernet/Gigabit passive optical network (EPON/GPON) and for the wireless last mile, long term evolution/5G (LTE/5G) is considered to be the perfect choice [8], [9]. We further incorporate an intelligent SAS along with LTE/5G in our proposal.

The EPON/GPON segment of the WOIN is a point-to-multipoint access network with no active elements in its distribution network. An EPON/GPON consists of an optical line terminal (OLT) located at a central office, a passive splitter (PS) and optical network units (ONUs) located in the user premises (Fig. 1). The ONUs are connected to the OLT via the PS, where the PS is a passive device and acts as a power splitter in the downlink and a coupler in the uplink. A multipoint control protocol (MPCP) based interleaved polling with adaptive cycle time (IPACT) is used as a statistical multiplexing technique for uplink [11]. The LTE/5G network, on the other hand, consists of BSs (eNodeBs for LTE and gNodeBs for 5G) and user equipments (UEs). The service gateway (S-GW) of the LTE/5G evolved packet core (EPC) is assumed to be directly connected to the OLT [9].

The SAS in the mobile network must be complemented by the EPON/GPON backhaul. Normally, bandwidth (BW) is over-provisioned while designing the EPON/GPON. Therefore, the higher traffic influx due to our proposed opportunistic wireless spectrum sharing scheme can be easily extended to the EPON/GPON. Thus, we also propose an end-to-end opportunistic BW allocation scheme in this paper. We point out the challenges and solution methodology for the problem in hand in the following sub-sections.

A. Challenges

1) Payment Based Fair and Opportunistic Scheduling: The spectrum sharing mechanism must guarantee the SLA of the PAL users. The remaining BW is allocated to the nomadic GAA users with the help of a fair competitive scheme. We opt for a payment-based competition in our spectrum sharing method.

In a spectrum sharing scenario, it is always desirable that the users (both PAL and GAA) are given more flexibility for deciding the fate of their own traffic. Even in a centralized spectrum sharing mechanism, the users should have the freedom of the payment that they want to offer for the transmission of their traffic.

Normally, an EPON is designed to deal with traffic that vary with time. However, in the present diverse user scenario, a user must be given admission to the network with an SLA. A PAL user has a long-term SLA while the GAA users are not assured of any data rate guarantee by the network. Further, we keep the provision that PAL users might also request for on-demand applications that are not covered by the SLA. Therefore, it must be ensured that if the generated traffic rate from a user exceeds the SLA, then the excess traffic is transmitted only when the user is willing to pay an additional amount. The excess traffic is the additional traffic required to support the on-demand applications. Thus, the user will have the option to decide the value of the additional payment depending on the importance of the packets in the user’s buffer. On the other hand, if SLA of any user is violated, the EPON should be imposed with a penalty. Thereby, the WOIN will also be conservative in BW distribution.

Finally, if it is agreed upon that a higher price must be paid for the packets that are above the SLA, the user fairness should also be maintained. Let us consider two scenarios.

1) Scenario A – The network load is low and only a single user is operating above SLA.

2) Scenario B – The network load is high, and more than one user is operating above SLA and the network can provide extra BW to a subset of users.

In scenario A, the user should be allocated BW in exchange of a minimum cost; since, there is surplus BW available. However, Scenario B is a competitive situation where several users must fight for a limited resource. In such a case, the BW should be allocated to the subset of users paying the highest amounts. Therefore, the network allocates BW to the highest paying users opportunistically depending on the scenario.

Unfortunately, for a user to decide on the fair payment value, information on the overall network load is required. By user fairness, it is intended to convey that if the network load is low and a user is requesting higher BW than mentioned in its SLA, then the payment per byte by the user should be lower than that of the payment requirement for a higher network load. In Fig. 2, we summarize the types of user present in the SAS, the types of traffic that they generate and the category of payments that they make for each traffic type.
2) Incomplete Network Load Information in WOIN Uplink: In WOIN uplink, the packets from the UEs of the LTE/5G network, reach the OLT of EPON via the ONUs. An enodeB/gNodeB is directly connected to an ONU in a WOIN to form a composite unit called ONU_{eNB}.\(^1\) Therefore, each ONU acts as a traffic aggregation point. In such a scenario, the transmission of a packet from a UE is not only affected by the other UEs directly connected to the same LTE/5G network but also the UEs that are associated to other LTE/5G networks or other ONUs of the same EPON. Therefore, ONUs collect the payments made by all the users to the OLT, it appears that the ONUs are the bidders of the OLT. Thus, ONUs should require huge overhead, which is not practical in an already constrained network. Hence, the users must devise some intelligent means to get around the problem and learn the network conditions over time.

Unfortunately, an ONU has no direct means of knowing the overall network load as it cannot interact with the other ONUs. Therefore, any user connected to a certain ONU via its LTE/5G network has no efficient means of perceiving the overall network load. The only way by which the vital traffic information might be exchanged over the WOIN network shall require huge overhead, which is not practical in an already constrained network. Hence, the users must devise some intelligent means to get around the problem and learn the network conditions over time.

Over the years, machine learning has been efficiently used to intelligently attune to network variability [12], [13]. We note that multiple entities (UEs) are trying to converge to an equilibrium decision point without interacting with each other. Therefore, it is evident that a distributed learning mechanism is required. On the other hand, the OLT performs uplink scheduling in the EPON without having detailed knowledge about the wireless traffic flows. Hence, in order to design an efficient end-to-end scheduling in the WOIN, we must ensure proper orchestration between the scheduling entities (SDN controllers) like the OLT in the EPON and the enodeB/gNodeBs in the wireless network.

B. Solutions

1) Learning Automata to the Rescue: Learning Automata is a stochastic multi-agent learning technique, which learns the optimal action through repeated interactions with its environment. It is therefore a perfect candidate for the given situation. LA is a distributed learning algorithm [7]. Hence, it can be independently executed in each UE. However, implementing LA in a UE is not recommended as it demands high processing power. Therefore, multi-access edge computing (MEC) may be employed where a MEC server hosted inside an enodeB/gNodeB runs the algorithm on behalf of the UEs with the help of the information received from the UEs [14]. An interested reader is directed to [7] for better understanding of LA.

Using LA, the UE learns the network conditions over time. The users can treat the actions of other users as environmental effect and thus observe the outcome against every action that it takes. Thus, LA can be achieved without any information exchange among the learning agents [7]. Slowly, the UE will converge towards equilibria point. This procedure has a finite convergence time. Luckily, in any practical time varying network, a load scenario remains approximately constant for a sufficient amount of time. Once, the approximate network load is learnt, a decision can be made on the payment.

The users declare the maximum payment per byte it is ready to make from time to time, which serves as the upper bound of the learned payment for the traffic. Thus, the problem of incomplete load information at the UE can be solved. This approach reduces the cost of UEs and also avoids transmission of large volumes of control information.

2) BW Is a Limited Resource and Traffic Has Delay Threshold: Section I.B.1 provides a way of abstracting the load information using LA. Thus, the users can decide on the payments to be made as per their requirements. However, we have not yet addressed the real problem posed by Scenario B mentioned in Section I.A. What if there are not enough resources to support all the contesting users? This is where the competitive distribution of resources using the Auction mechanism comes in. In this approach, the UEs serve as the LA equipped bidders and the OLT serves as the auctioneer. However, the UEs are connected to the OLT via the ONUs. Therefore, ONUs collect the payments made by all the users connected to it and forwards a composite bid to the OLT. Thus, to the OLT, it appears that the ONUs are the bidders of the BW.
For smooth operation, the OLT must ensure truthful bidding in order to carry out a fair allocation. Therefore, second-price auction or Vickrey auction is the obvious choice in the given situation [15]. Further, as multiple BW units are to be allocated to multiple ONUs; therefore, Vickrey-Clarke-Groves (VCG) mechanism is more suited for such an allocation procedure [16].

C. Contributions

To summarize, in this paper, we have proposed a Learning automata aided auction based opportunistic resource allocation (AuORA) protocol. The proposal jointly optimizes the resource allocation in the wireless and optical network segments of the WOIN and ensures end-to-end SLA. The proposal facilitates the network operation in the following way:

- The LA based SLA aware algorithm (LASA) optimizes an UE's perception of the network with zero interaction with the other UEs. Thereafter, the UEs aid the ONUs in the bid evaluation process such that the end-to-end QoS of traffic classes involved can be maintained.
- The end-to-end allocation mechanism maintains economic fairness, i.e., when the network load is less, the payment per byte for on-demand traffic is less; whereas the payment for the same becomes more competitive when the network load increases. Our integration of LA with VCG ensures that this is fairly mechanized from the central controller (i.e., the OLT). VCG is also converted into an optimization due to the distributed learning procedure of LA.
- A traffic shaping and assignment algorithm (TSA) has been proposed that identifies the SLA traffic and the on-demand traffic. The TSA algorithm also performs resource allocation in the wireless uplink. However, in contrast to the throughput-based resource allocation present in the literature, the resource allocation proposed in this work is an economic allocation.

The rest of the paper is organized as follows. Section II throws light on the available literature. Section III describes the system model and the primary objectives. Section IV provides details of the proposed algorithms. Section V discusses the algorithmic complexity of the proposal. Section VI introduces the simulation model. Section VII showcases the results and discussion followed by the conclusion.

II. RELATED WORK

In this section, we provide a brief overview of the available literature on SAS and also on the QoS and SLA based dynamic BW allocation (DBA) for EPON. Thereafter, we provide a gap analysis of the available literature.

A. Spectrum Access System

Several research works are available in the literature that is targeted towards dynamic spectrum sharing between higher priority primary users and lower priority secondary users. The authors of [17] have proposed a learning aided listen-before-talk scheme for the GAA users to access the spectrum. However, the central idea of the scheme being distributed in nature may impart interference to the PAL users if the GAA users are not able to perfectly predict PAL activity. In [18], we find a resource allocation scheme between fixed and mobile GAAs while limiting the interference to the PALs. In [19], we find price-based service agreements based on incumbent and licensee spectrum usage. The authors of [20] present a distributed power allocation algorithm for the GAA users so that the interference caused by the GAA users to the PALs can be minimized while at the same time the need for sharing the location information of the GAA users can be avoided. Since, the MNOs might be reluctant to share detailed location information of the BSs/users, the authors of [4] discusses a method where the mathematical distribution of the lower-tier network users and the number of lower-tier transmitters are shared with the higher-tier network users. Thereby, the higher-tier network users can estimate the aggregated interference from the lower-tier network users and thereafter design exclusion zones for the lower-tier network users. However, their solution is in the average sense, as they involve mathematical distribution of the lower-tier users. In [21], the GAA users are accommodated in the unused resources after the PAL users have been allocated. However, the allocation is performed over multiple timeslots and therefore, GAA transmission might be halted as soon as a PAL user requests a resource currently allocated to the GAA user. The problem of arrival of PAL user resulting in halting of GAA transmission is solved using artificial neural networks in [22], where the arrival of the PAL users is predicted before the GAA user allocation. Unfortunately, the method presented in [22] works only for a single channel/resource block. We find a distributed power allocation scheme for the GAA users to keep the aggregated interference to the PAL users within limits in [23]. A method for determination of optimal exclusion zone for the GAA user is presented in [24]. The approach relies on sharing of the distribution and maximum number of transmitters in a finite area by the GAA.

B. SLA Based DBA for EPON

The authors of [25] propose two algorithms to maintain QoS; Modified delay aware window sizing (M-DAWS) for high-priority traffic and delay aware grant sizing (DAGS) for medium-priority traffic. They further propose an SLA aware differential polling (DP) algorithm. DP algorithm divides the user into multiple groups based on the delay bound of the highest priority packets. A P2P live-streaming architecture is proposed where the delay bound is efficiently met in a stand-alone EPON. The authors of [27] propose a fair excess-dynamic BW allocation (FEX-DBA) that is based on a network utility maximization model. FEX-DBA is an online scheduling algorithm that works efficiently in a stand-alone EPON. The authors of [28] propose an evolutionary game-based approach to share the PON backhaul between two competing BSs. They argue that fixed allocation of PON resources is inefficient while satisfying the dynamic requirements of the BSs. However, they do not consider the traffic of the individual UEs.

In [29], a dynamic BW allocation algorithm with demand forecasting has been proposed. The proposal reduces the end-to-end delay by using statistical modelling to forecast
future BW demands in a 10-gigabit-capable passive optical network. A resource management procedure for optimizing the allocation of GPON resources based on the dynamic adjustment of the SLA parameters according to estimated customer traffic patterns has been proposed in [30]. The work utilizes clustering analysis to segregate users according to their network uses based on real-time and historical data. A joint BW and queue management mechanism for upstream SLA-Oriented QoS in Multi-Tenant and Multi-Service PONs is explored in [31]. The authors of [32], propose a double fair dynamic BW allocation scheme based on user satisfaction. The proposal accommodates fairness both in terms of wavelength allocation and time-slot allocation.

C. Gaps in Literature

The available literature on SAS or EPON concentrates on just the wireless or optical network part respectively. The works do not consider the circumstances that may arise if the wired backhaul fails to forward the data received by the wireless BSs. Moreover, the works on SAS consider distributed access mechanisms for the GAA users. It is well-known that distributed systems must adhere to strict co-ordination to function efficiently. In a WOIN, a centralized spectrum allocation methodology is often useful for providing end-to-end service guarantee. Similarly, in the EPON literature, most of the papers mainly focus either on QoS enhancement or providing a SLA based treatment. However, to the best of our knowledge, end-to-end opportunistic scheduling in WOIN/EPON has not been considered in the literature. Therefore, we come up with a new end-to-end scheduling strategy in WOIN that can satisfy SLA requirements of SAS.

III. SYSTEM MODEL AND OBJECTIVES

In this section, we illustrate the system model and declare the functionalities of different components of the network (see Fig. 3). The OLT performs BW allocation in the EPON and the enodeB/gNodeB is responsible for BW distribution in the LTE/5G network. Thus, the OLT with the help of the enodeB/gNodeB performs the functions of the SAS controller. The SAS Controller is supported by the intelligent users that employs LA. The primary objectives of the proposal are described in the following sub-sections.

A. End-to-End QoS Maintenance

Our proposal enforces SLA in order to provide end-to-end QoS. During connection establishment, the ONU and the users agree upon an SLA in exchange of a base fare. SLA is defined in terms of average bit rate. If a user operates within the decided SLA, the ONU must provide enough BW to the user to meet the SLA. Finally, if the ONU fails to provide transmission opportunity for the SLA packets of a certain user, the ONU has to pay a penalty to the user. In this work, we assume that the PAL users have an SLA with the possibility of trying to transmit more data than their SLA. On the other hand, the GAA users have no SLA guarantees. They transmit traffic opportunistically.

B. Opportunistic BW Allocation

Opportunistic BW allocation takes place in the EPON side of the network. After receiving the packets from the users, the ONU tries to forward the packets that are above the SLA (ASLA packets (bytes)). When the BW demand for the ASLA packets is higher than the available BW, the BS provides a competitive basis with the help of an auction. The auction is held only on the BW available after the transmission of the SLA packets. BW is allocated in chunks, i.e., the total BW is divided into finite number of chunks. Therefore, we have a multiple item (chunk) auction with multiple bidders (ONUs). The OLT allocates the chunks to the highest bidders.

In this paper, the packets from the PAL users are classified as SLA or ASLA packets depending on the volume of their traffic transmission over a finite observation window. However, the packets from the GAA users are always marked as ASLA packets as they don’t have any SLA.

IV. THE END-TO-END SCHEDULING

In this section, we describe our proposed TSA, LASA and AuORA. In Fig. 4, we provide a high-level overview of the proposal. The conjunction of the algorithms facilitates an end-to-end information flow while avoiding huge volumes of control information exchange between the network nodes (OLT, ONU and UEs). Both LASA and AuORA can be used for single as well as mixed traffic. Further, if not mentioned otherwise, we shall denote both the PAL and the GAA UEs as UEs from this point onwards.

A. Traffic Shaping and Assignment Algorithm

1) Traffic Shaping at the enodeB/gNodeBs: In the LTE/5G side, the enodeB/gNodeBs employ TSA. A separate instance of TSA is executed by the enodeB/gNodeB for every single UE. TSA directs that the UE $i$ will pay a base price per byte ($\chi_i$) till its uplink transmission is within the SLA. However, as the BW requirements of the UE exceed its SLA, the UE has to pay a higher amount per byte. This “increased rate” is a multiple of the base rate.
The $i^{th}$ UE sends the number of bytes in its buffer ($\beta^t_i$) (see Fig. 4). The UE also informs the enodeB/gNodeB, the maximum price it is willing to pay per byte.

The enodeB/gNodeB keeps track of the number of SLA bytes that UE $i$ has transmitted over last $(M-1)$ time steps ($\phi^t_i$) (see storage block of Fig. 4). The count is only kept for the transmissions that are within the SLA, which is defined in terms of average bit rate. Let, $\Omega_i$ represent the number of bytes that should be transmitted by UE $i$ over the last $M$ time steps to meet SLA.

$$\phi^t_i = \sum_{j=t-M}^{t-1} T^k_{S\!L\!A,i}; \Omega_i = M \Gamma_{S\!L\!A,i}$$

where, $\Gamma_{S\!L\!A,i}$ is the number of bytes that should be transmitted by UE $i$ over a single time slot to meet SLA and $T^k_{S\!L\!A,i}$ is the number of SLA bytes that has been transmitted by UE $i$ in the $k^{th}$ time step. Thus, in every time step, ($\phi^t_i$) plus the number of bytes present in the UE $i$’s buffer ($\beta^t_i$) are checked against ($\Omega_i$) by the traffic shaper (see Fig. 4). This step leads to the evaluation of number of SLA and ASLA bytes for UE $i$ ($\beta^t_{S\!L\!A,i}$ and $\beta^t_{A\!S\!L\!A,i}$ respectively). This may give rise to three cases:

1) $\phi^t_i \geq \Omega_i$ – Here, all the bytes in the buffer are marked as ASLA packets ($\beta^t_{S\!L\!A,i} = 0; \beta^t_{A\!S\!L\!A,i} = \beta^t_i$).
2) $\phi^t_i + \beta^t_i \leq \Omega_i$ and $\phi^t_i < \Omega_i$ – Here, ($\beta^t_{S\!L\!A,i} = \Omega_i - \phi^t_i$) bytes in the buffer are marked as within SLA and the rest of the bytes are marked as ASLA ($\beta^t_{A\!S\!L\!A,i} = \beta^t_i - \beta^t_{S\!L\!A,i}$).
3) $\phi^t_i + \beta^t_i \leq \Omega_i$ – In this case, all the bytes present in the buffer are marked as within SLA ($\beta^t_{S\!L\!A,i} = \beta^t_i; \beta^t_{A\!S\!L\!A,i} = 0$).

Once, the number of ASLA bytes ($\beta^t_{A\!S\!L\!A,i}$) has been calculated, the next step is to calculate the buffer states. The buffer states are normalized value of the $\beta^t_{A\!S\!L\!A,i}$ w.r.t buffer capacity and is found by $\text{ceil} \left( \frac{\beta^t_{A\!S\!L\!A,i}}{\text{|S|}} \right)$, where $|S|$ denotes the number of buffer states and $C_i$ is the buffer capacity. Depending on the current state, a payment value is being evaluated. The payment value ($P_i$) is probabilistically decided by using the input from the LASA algorithm (to be discussed in Section IV-B). As outlined in Fig. 4, the selected payment value acts as the input to the assignment module of the enodeB/gNodeB.

2) Price-Based Assignment by the enodeB/gNodeB: In this sub-section, we describe the assignment-based procedure that we employ to schedule the UEs. In this phase, the assignment module of the enodeB/gNodeB (see Fig. 4) maximizes the earnings in the process of scheduling. We adopt the primary principle of BW scheduling from our previous works [33], [34]. However, unlike [33], [34], we are performing a price-based assignment where the bid price is obtained from the learning module.
First, the entire BW is broken into discrete non-overlapping BW units called resource chunks (RCs). One RC can be allocated only to a single UE. Therefore, the enodeB/gNodeB first calculates the number of bytes that can be transmitted by a UE over each of the RCs provided the RC is being allocated to the UE. Logically, this value is the minimum of the number of bytes present in the UE buffer and the transmission of number of bytes that the RC physically allows after considering the channel conditions. This calculation leads to the formation of the traffic matrix $W$. The number of bytes that can be transmitted is given by (2).

$$w_{i,j} = \min (q_{ij}, \beta_i) \tag{2}$$

where, $w_{i,j}$ is the element of traffic matrix $W$ that corresponds to the $i^{th}$ UE and the $j^{th}$ RC; $q_{ij}$ is the maximum possible number of bytes that the $i^{th}$ UE can send on the $j^{th}$ RC and $\beta_i$ is the number of bytes present in $i^{th}$ UE’s buffer.

Thereafter, each of the elements of the $W$ matrix is multiplied with the payment per byte that is to be received from the UE if the UE is allocated to that RC. Hence, three distinct cases may arise for which the payments to be received from the UE ($P_{i,j}$) are calculated as:

1. If $\phi_i^t \geq \Omega_i$ then $\rho_{i,j} = P_i w_{i,j}$.
2. If $\phi_i^t + w_{i,j} > \Omega_i$ and $\phi_i^t < \Omega_i$ then $\rho_{i,j} = (\Omega_i - \phi_i^t) \lambda_i + (w_{ij} - \Omega_i + \phi_i^t) P_i$.

$\phi_i^t$ is the number of bytes present in the $i^{th}$ UE and the $t^{th}$ time step. $\Omega_i$ is the element of traffic matrix $\Omega$ that corresponds to the $i^{th}$ UE and the $t^{th}$ time step.

**Algorithm 1 TSA Algorithm**

Input: $\chi_i, \beta_i, \phi_i^t, \Omega_i, C_i, [S], q_{ij}, \tilde{M}$

Output: $P_i$

1. Classify packets;
2. Identify state $s_i$;
3. Select action $a_i$ from the set $A_i$;
4. Execute scheduling;
5. if UE $i$ is scheduled
6. Buffer the incoming packets;
7. Calculate the received price;
8. else
9. Call LASA (Algorithm 2);
10. end if.

* TSA is operated at the enodeB/gNodeB module of the ONU in every TTI (1 ms)

3) If $\phi_i^t + w_{i,j} \leq \Omega_i$, then $\rho_{i,j} = \chi_i w_{i,j}$.

Please note that the distinction between the above cases and the ones described in Section IVA.1 is in the fact that the total received payments are estimated based on the number of bytes that can be transmitted. On the other hand, in Section IVA.1, we illustrate the packet identification procedure into SLA and ASLA packets.

It is essential that the UEs that are still within their SLA and their SLA packets have a risk of being dropped should be given a preferential treatment in the scheduling. Therefore, we ensure that if a user having SLA packets is not allocated in the current cycle and some of its packets are dropped, the enodeB/gNodeB has to give a penalty. In graphical terms, we make the weight of connecting the UEs to the dummy RCs as the penalty value. The penalty is negative of the number of SLA bytes that will be dropped by UE $i$ ($\psi_i$) multiplied by a number larger than the highest payment level ($\bar{P}$). We have taken $\bar{P} \in Z^+$ as $\bar{P} = P_i + 1$. This approach is taken to ensure than an SLA user is given more priority than an ASLA user. Once the entire matrix is formulated, the enodeB/gNodeB runs a maximization algorithm (ILP 3-8) to evaluate the allocation.

$$\text{Maximize } \sum_i \sum_j \alpha_{ij} \rho_{i,j} - \sum_i \gamma_i \bar{P} \psi_i \tag{3}$$

Subject to,

$$\sum_i \alpha_{ij} = 1, \forall j \tag{4}$$

$$\sum_j \alpha_{ij} \leq 1, \forall i \tag{5}$$

$$\gamma_i + \sum_j \alpha_{ij} = 1, \forall i \tag{6}$$

$$\alpha_{ij} = 0 \lor 1 \tag{7}$$

$$\gamma_i = 0 \lor 1 \tag{8}$$

where, $\rho_{i,j}$ is the payment that the UE $i$ will make to the enodeB/gNodeB if UE $i$ is allocated to RC $j$; $\alpha_{ij}$ is a binary variable, which is equal to 1 if UE $i$ is allocated to RC $j$.

2) The assignment problem of network allocation requires equal number of elements in both the parties, i.e., the number of UEs ($N$) should be equal to the number of RCs ($M$). However, in most of the cases, $N > M$. Therefore, in order to make the cardinality of both the parties same, $(N - M)$ dummy RCs are added. Any UE assigned to a dummy RC will not receive any BW in the current cycle.
Therefore, if there is no ambiguity, we will be dropping the suffix following discussion.

From the action space a higher price level is more likely to be chosen. Alternatively, in heavy network loads, one levels of payment values over the base price. Concerned UEs is the only way to award BW to the UE that UEs contending for the extra BW, a competition among the concerned UE. On the other hand, if there are several load is relatively low but one UE requires more BW than its network load conditions properly. For example, if the network values according to the state of the queue. We observe that choosing the payment values using the LA algorithm [7], [35]. (see Fig. 4) of an enodeB/gNodeB updates the probability of summarized in Algorithm 1.

The LA algorithm runs only for the

packets.4 The LA Based SLA Aware Algorithm at the enodeB/gNodeB:3

In this sub-section, we describe how the learning module (see Fig. 4) of an enodeB/gNodeB updates the probability of choosing the payment values using the LA algorithm [7], [35]. As already mentioned, we allow multiple levels of payment values according to the state of the queue. We observe that including a single level of payment value may not capture the network load conditions properly. For example, if the network load is relatively low but one UE requires more BW than its prescribed SLA, it is not fair to charge a huge amount from the concerned UE. On the other hand, if there are several UEs contending for the extra BW, a competition among the concerned UEs is the only way to award BW to the UE that is willing to pay more. Hence, we have included more than one levels of payment values over the base price.

We employ LASA for the UEs to decide which of the available price levels to use. As the network operation progresses, the instances of the LA algorithm running in the learning module of the enodeB/gNodeB converge to the optimal pricing option. Therefore, if the overall network load is low, there will be fewer number of competing UEs and hence, a lower price level will be chosen. Alternatively, in heavy network loads, a higher price level is more likely to be chosen.

The LA algorithm runs only for the \( \beta_{\text{ASLA}} \) packets.4 The descriptions of the variables used in the LA are given in Table II. The initial probability of choosing all the actions from the action space \( A_s \) are equally likely. Hence, the initial condition for the LA algorithm is given by (9).

\[
p_0^a = \frac{1}{|A_s|}, \quad \forall a \in A_s
\]  

where, \( p_0^a \) is the probability of choosing action \( a \) in the \( t^{th} \) time step, \( |A_s| \) denotes the number of available actions in a given state \( S \). Please note that an action \( a \) corresponds to a price level and a buffer state \( S \) signifies a normalized value of the \( \beta_{\text{ASLA}} \) for UE \( i \) w.r.t buffer capacity as introduced in Section IV A.1.

During the course of learning, the agent updates \( p_{t+1}^a | a \in A_s \) at each time step (\( t \)) based on the outcome of the last decision (\( B = 0 \) (success) or 1 (failure)). The outcome is the reward or penalty (\( R_a \) or \( L_a \)) received by the UE after choosing the action \( a \). The outcome of the decision depends on the requested and the received BW from the ONU and also on whether the ONU is able to forward the received packets to the OLT. As a result, two cases arise –

1) The UE gets the requested BW — In this case, the UE gets the requested BW for the ASLA bytes from the ONU. As a result, the packets are transmitted to the ONU. However, the packets received by the ONU may or may not be further forwarded to the OLT depending upon the load condition in the EPON. If the EPON load is excessive, the packets are dropped at the ONU as the packets overshoot their delay deadline. On the other hand, if the EPON load is low, the ONU will successfully forward all the packets to the OLT. Therefore, to provide end-to-end packet delivery information, the ONU provides the update for this set of packets after it successfully forwards to the OLT or drops them. In such a situation, the probability update is performed only after receiving the packet drop information from the ONU.

2) The UE does not get the requested BW — If a UE is not allocated enough BW to transmit any ASLA packets in the present TTI, the probability update is performed immediately.

If all the ASLA packets reach successfully to the OLT, the outcome is considered as a success event and reward is generated. Otherwise, the outcome is considered as a failure and penalty is generated. Let, \( T^i \) be the number of bytes from the \( t^{th} \) time interval that can be transmitted by the ONU and \( P^t \) be the payment per byte in the \( t^{th} \) time interval. The value of \( R_a \) and \( L_a \) are:

\[
R_a = \frac{\beta_{\text{ASLA}}}{P^t}, \quad \text{if } T^i \geq \beta_{\text{ASLA}} + \beta_{\text{SLA}}
\]  

We remind the readers that the MEC servers situated in an enodeB/gNodeB execute the LA algorithm on behalf of the UEs.

| SYMBOLS | DESCRIPTION |
|---------|-------------|
| \( A_s \) | Set of available actions (set of price levels) in state \( S \). |
| \( p_0^a \) | Probability of choosing action \( a \in A_s \) in the \( t^{th} \) time step for UE \( i \). |
| \( \Xi_{A_s} \) | Probability vector for \( A_s \) for UE \( i \). |
| \( R_a \) | Reward after taking action \( a \) for UE \( i \). |
| \( L_a \) | Penalty after taking action \( a \) for UE \( i \). |
| \( B \) | Variable that records success (\( B = 0 \)) or failure (\( B = 1 \)). |

Algorithm 2 LASA

**Input:** \( \beta_{\text{ASLA}}, \beta_{\text{SLA}}, T^i, \Xi_{A_s} \)

**Output:** \( R_{a,i} \)

1: If \( T^i \geq \beta_{\text{ASLA}} + \beta_{\text{SLA}} \):
2: Calculate \( R_{a,i} \);
3: Calculate normalized value of \( R_{a,i} \);
4: \( B = 0 \);
5: else
6: Calculate \( L_{a,i} \);
7: Calculate normalized value of \( L_{a,i} \);
8: \( B = 1 \);
9: Update action probability vector \( \Xi_{A_s} \), i.e., \( p_{t+1}^a | a \in A_s \) ∈ \( \Xi_{A_s} \).

* LASA is operated at the enodeB/gNodeB module of the ONU.
For the purpose of the algorithm, the Reward (and penalty) value \((R_a)\) is normalized.\(^5\) We use the normalized value to update the values of \(p_i^t.\)^\(^6\)

In our case, we have multiple UEs (agents). Every single agent takes its actions independently. Moreover, any UEi has no information about the actions taken by UEs \(j\) where \(j \neq i\). The UEi considers all the outcomes due to the actions taken by the other UEs as environmental factor. UEi therefore gets an abstract view of the environment conditions without having to interact with any other UE.

\(\text{C. Auction Based Opportunistic Resource Allocation Algorithm}\)

1) An Offline Protocol: AuORA is an offline protocol as it considers the information from all the ONUs while taking the scheduling decision. It follows report before data format, i.e., report is transmitted at the beginning of the transmission slot. This approach helps in reducing the idle time created between cycles due to DBA processing. It is expected that if report before data is used and the nearest ONU is polled first then there will be very little idle time. We believe that other options like performing DBA just after receiving the report message from the \((\Phi - 1)\)th ONU is not advisable as the results would become sub-optimal. Here, \(\Phi\) is the number of ONUs. For better performance, one can schedule the ONU with the largest transmission window at the end of the cycle.

2) Report Preparation: Bid preparation is the most essential part of the AuORA protocol (see Fig. 4). The entire responsibility of preparation of bids lies with the ONU, since they are the bidders/purchasers of BW from the OLT. According to AuORA, every ONU must follow the same guidelines; e.g. if an ONU need more BW, it has to pay more.

The bids are simply created by summing up the total payment received by the enodeB/gNodeBs from the UEs for the ASLA packets.

\[v_n = \sum_{i \in J} p_i\]

where, \(v_n\) is the bid value of the \(n\)th ONU, \(P_i\) is the payment received for packet \(i\) and \(J\) is the set of ASLA packets.

Our proposal indirectly incorporates the load scenario in the LTE/5G network while performing scheduling in EPON. Therefore, if there is any urgent packet from the LTE/5G

\[L_a = \begin{cases} (T^t - \beta^t_{\text{ASLA}} - \beta^t_{\text{SLA}}) P^t, & \text{if } \beta^t_{\text{ASLA}} + \beta^t_{\text{SLA}} > T^t \geq \beta^t_{\text{SLA}} \\ -\beta^t_{\text{ASLA}} P^t, & \text{otherwise} \end{cases} \quad (11)\]

side, it will come with a higher payment and will be given a preferential treatment. Further, the ONU must also ensure that it can transmit the SLA packets. Thus, once the SLA packets are transmitted, we ensure an expedited treatment to any ASLA packet seeking immediate transmission. Thus, the \(n^{th}\) ONU reports the number of SLA packets, the number of ASLA packets and the bid for the BW purchase. The format of the report for the \(n^{th}\) ONU is \((R_{\text{SLA},n}, R_{\text{ASLA},n}, v_n)\), where, \(R_{\text{SLA},n}\) is the number of BW chunks required to transmit the SLA packets, \(R_{\text{ASLA},n}\) is the number of BW chunks required to transmit the ASLA packets and \(v_n\) is the bid value. A BW chunk can be as small as a single byte. In any case, the total number of BW chunks available in the system is restricted by the cycle length, which is 2 ms in our case.

Since, we operate VCG auction mechanism [38]; the ONU that wins the BW will always pay an amount which is less than its bid. Hence, the profit of the ONU is the difference between the bid that it places and the actual payment that it makes to the OLT. Further, please note that the valuation of the ONU is equal to the bid value (which is obtained from the payment from the UEs). This happens because VCG ensures truthful bidding.

3) Queue Management: In order to maintain proper QoS, the ONU maintains three queues. The first one is for highest priority real-time traffic (voice), the second one is for the medium priority real-time traffic (video) and the third one is for best effort traffic (data). The packets in the real-time queues are arranged in the order of their arrival.

Upon receiving a packet, we assign a weight and value to it. Typically, the weight of the \(i^{th}\) packet \((w_i)\) is its size and the value \((\vartheta_i)\) is the payment received from the UE for that packet. These stored values serve two purposes. Firstly, they help in the Report message generation. Secondly, they help in the procedure of marking a packet for transmission.

We mention here that we do not follow strict priority scheduling where packets from a lower priority queue are transmitted only when all its higher priority queues are empty. We maximize the payment received by transmitting the most valued packets. The packets that are marked to be transmitted in the current cycle may belong to any of the three queues. Further, the SLA packets are always transmitted before the ASLA packets.

4) VCG Auction and BW Allocation: The responsibility of BW allocation lies with the OLT. First, the OLT reserves the BW required for transmission of the SLA packets. This step is taken in order to ensure that an ONU is not starved because of richer and BW hungry ONUs.

Having received all the bid values \((v_n)\) and reserving the BW for ASLA packets for all ONUs, the OLT initiates the allocation procedure for the excess BW.

Please note that the allocation is essentially a fractional knapsack problem. In a fractional knapsack problem, whole items are inserted in the knapsack as long as possible. Finally, when there is not enough capacity left in the knapsack to insert a whole item, a fraction of the item is inserted into the

\[^5\]R_{a,norm} = \frac{R_a - R_{a,\text{min}}}{R_{a,\text{max}} - R_{a,\text{min}}} \text{ where, } R_{a,\text{min}} = 0 \text{ is the minimum possible value of } R_a \text{ and } R_{a,\text{max}} = \beta^t_{\text{ASLA}} \text{ is the maximum possible value of } R_a. \text{ Similarly, the penalty } (L_a) \text{ is also normalized with } L_{a,\text{min}} = -\beta^t_{\text{ASLA}} P^t \text{ and } L_{a,\text{max}} = 0.

\[^6\]p_a 1 = p_a + R_{a,norm} [1 - p_a] 

\(p_{i+1} = (1 - R_{a,norm}) p^t \text{ if } j \neq a\) 

\(p_{i+1} = (1 - R_{a,norm}) P^t \text{ if } j \neq a\) 

\(p_{j+1} = \frac{L_{a,norm} + (1 - L_{a,norm}) p^t}{p_a} \text{ if } j \neq a\)
knapsack. The problem is defined as,
\[
\begin{align*}
\text{Maximize} & \quad \sum_n \alpha_n v_n \\
\text{Subject to,} & \quad \sum_n \alpha_n R_{ASLA,n} \leq C \\
& \quad 0 \leq \alpha_n \leq 1
\end{align*}
\]

where, \( C \) is the BW left after taking care of the SLA packets, \( R_{ASLA,n} \) is the requirement of the \( n \)th ONU and \( v_n \) is the price that the \( n \)th ONU is prepared to pay on receiving the allocation. \( \alpha_n \) is a decision variable where, \( \alpha_n = 0 \) indicates that the \( n \)th ONU is not allocated any BW. On the other hand, \( 0 < \alpha_n \leq 1 \) indicates allocation.

It is well known that a fractional knapsack problem can be optimally solved using a greedy algorithm after sorting the items in a decreasing order of the ratio \( \frac{v_n}{R_{ASLA,n}} \). Then, the allocation is done following the evaluated order.

Once, the allocation is completed, the next step is to receive the payment from an allocated ONU in exchange of the number of BW chunks. The payment evaluation is computed according to the principles of VCG auction mechanism. VCG is a second price auction and therefore, the concerned ONU (an agent in auctioning terms) has to pay a sum which is lower than its bid value (discounted value) [36]. The idea behind the discount is that an allocated agent makes a contribution to the system. If the agent was not present in the system, the system would have collected lesser profit. Hence, the agent is given a discount over its bid value that is equal to the profit that is earned by the system due to the presence of the agent in the system. This discount is the profit of the ONU in the packet transmission.\(^7\)

5) Packet Transmission: This sub-section describes the policy adopted for marking a packet so that it can be transmitted in the current cycle. First, the SLA packets are marked for transmission and the BW required for their transmission is deducted from the total available BW. Thereafter, the ONU selects the packets having the highest payments from the three queues. In other words, the ONU seeks to maximize the profit earned by sending its buffered packets by fitting them into the remaining BW. This requirement matches with that of a knapsack problem. The problem is formally defined as follows.
\[
\begin{align*}
\text{Maximize} & \quad \sum_i \sum_j \alpha_{ij} \theta_{ij} \\
\text{Subject to,} & \quad \sum_i \sum_j \alpha_{ij} w_{ij} \leq G \\
& \quad \alpha_{ij} = 0 \text{ or } 1
\end{align*}
\]

\(^7\)Let \( k^*_n \) and \( k^*_n \) be the optimal assignments when the \( n \)th ONU is present and absent respectively. Similarly, let \( \varphi (k^*_n) \) and \( \varphi (k^*_n) \) be the prices of the resources as per the bid values. Therefore, the profit brought by \( n \)th ONU is given by:
\[
\tau_n = \varphi (k^*_n) - \varphi (k^*_n)
\]

Hence, the auctioneer gives a discount of \( \tau_n \) to \( n \)th ONU and the price that the \( n \)th ONU needs to pay is given by:
\[
H_n = \left( \frac{\tau_n}{R_{ASLA,n}} \right) \varphi_n - \tau_n
\]

where, \( \varphi_n \) is the number of chunks allocated by the VCG auction to the \( n \)th ONU.

\[\text{Algorithm 3 AuORA}\]
\[
\begin{align*}
\text{Input: } & P_i \\
\text{Output: } & T_i
\end{align*}
\]
\[
\begin{align*}
1: & \quad \text{Prepare Bids;} \\
2: & \quad \text{Receive Grant from OLT;} \\
3: & \quad \text{Check for delay deadlines of the packets;} \\
4: & \quad \text{if packet delay is within deadline} \\
5: & \quad \text{Forward packets to OLT if Bandwidth is available;} \\
6: & \quad \text{Update } T_i; \\
7: & \quad \text{else} \\
8: & \quad \text{Drop packet;} \\
9: & \quad \text{end if;} \\
10: & \quad \text{if all packets received from a particular UE in a single TTI are either forwarded or dropped;} \\
11: & \quad \text{Call LASA(Algorithm 2);} \\
12: & \quad \text{end if;} \\
\end{align*}
\]

where, \( j \in \{\text{voice, video, data}\} \), \( \alpha_{ij} \) is a binary variable indicating the scheduling information of the \( i \)th packet of the \( j \)th type, \( \theta_{ij} \) is the value associated with the \( i \)th packet of the \( j \)th type, \( w_{ij} \) is the size of the \( i \)th packet of the \( j \)th type and \( G \) is the allocated BW.

In order to minimize the execution time of the algorithm, the knapsack algorithm is executed with the help of greedy algorithm. Greedy algorithm works perfectly when there is divisible item in the knapsack (fractional knapsack). Unfortunately, in EPONs, a packet cannot be divided and hence, knapsack should ideally be solved using dynamic programming. However, using dynamic programming makes the processing of the problem beyond practical limits. Therefore, even though greedy gives slightly sub-optimal results, we use it for solving the knapsack. We believe that the ONU will have finite number of packets to deal with while solving the knapsack and hence the processing time complexity will remain within practical limits.

6) Reward/Penalty Feedback: This sub-section deals with the details of how the ONU gives reward/penalty feedback to the LASA module of the ONU in order to aid the LA algorithm (see Fig. 4). As we have already mentioned, a packet received over the wireless interface may get dropped in the EPON. In such a situation, the ONU must return the payment received from the concerned UE and provide feedback such that the UE becomes more successful in the subsequent attempts. Therefore, ONU records the information about the status of the packets after they are transmitted or dropped. The ONU feeds this value to the LA framework with the correct action (bid value) so that the action probabilities \( (p^*_{\tau^2 + 1}) \) can be updated for the next time slot. The steps of AuORA are listed in Algorithm 3.

V. NOTE ON ALGORITHMIC COMPLEXITY

The traffic shaping algorithm has a complexity of \( O(n) \), where \( n \) is the number of UEs. The creation of the traffic matrix has a worst-case complexity of \( O(mn) \), where \( m \) is the number of RCs and \( n \) is the number of UEs. Therefore, for creating a symmetric matrix, the complexity becomes \( O(max(m,n)^2) \). The traffic matrix creation
The simulation model has been developed using OMNeT++ network simulator. The EPON has been built according to the guidelines given in [11]. The parameters used in the simulation are summarized in TABLE III.

A seven-cell scenario has been considered in the LTE/5G network, where a single cell is surrounded by six first tier cells. The work assumes that the center cell is the serving cell and the first-tier cells provide the interfering signal power. All the measurements have been taken in the center cell and only the packets coming from the center cell are fed to the EPON. However, as the throughput from the center cell is limited to 10 Mbps, we have used 90% of the EPON link for background traffic and only 10% of the EPON capacity is used for backhauling the LTE/5G traffic. The UEs have been deployed in the cells by following a Poisson point process. Uplink transmission power control and MCS have been considered as per the guidelines provided in [39]. Block fading channel model has been used, where the channel conditions remain constant over a TTI [34]. The details of the simulation parameters are listed in TABLE IV.

We have used a single class of traffic for illustrating the performance of AuORA. However, the simulation can be easily extended to multiple traffic with varying priorities.

### A. Benchmarks

For the comparisons, we have used the following protocols in the LTE/5G uplink –

- **Dynamic Hungarian Algorithm with Modification (DHAM)** [33] – DHAM is a buffer and channel aware uplink scheduling algorithm for LTE. To the best of our knowledge, DHAM is the most efficient uplink scheduling protocol available.
- **Adaptive and potential aware scheduling scheme (APASS)** [40] – One of the recent buffer and QoS aware throughput maximization algorithm for LTE uplink.
- **Max_PRB** [21], [22] – Max_PRB is one of the recent dynamic SAS scheme that utilizes the white spaces (unallocated resources of the LTE system) after scheduling the PAL users.

For the EPON, we have used two different protocols for the comparative studies –

- **Interleaved Polling with Adaptive Cycle Time** [11] – IPACT is one of the most famous and standard protocol used in the EPON uplink. Therefore, it is one of our automatic choices for the benchmarking.
- **Fair excess-dynamic BW allocation** [27] – To the best of our knowledge, FEX-DBA is the most recent protocol available in the literature that deals with SLA based fair scheduling protocol for EPON uplink.

### VII. RESULTS AND DISCUSSIONS

#### A. End-to-End Performance

The performance of the AuORA algorithm working in tandem with LASA has been evaluated and discussed in this sub-section. Through simulations, we find that the LASA along with the AuORA (LASA-AuORA) algorithm transmits majority of the SLA packets even when the network load is high. The result is evident in the number of SLA packets dropped plots of Fig. 5 and Fig. 6. This happens because AuORA ensures that the SLA packets are first transmitted in every cycle. However, we observe a very low percentage of SLA packets being dropped at heavy network loads because the packets have already suffered high delay in the LTE/5G network and cannot wait for even the very first transmission opportunity in the EPON. The combination of maxPRB and IPACT provides comparable performance in terms of delivery of SLA packets as maxPRB prioritizes transmission of SLA packets. On the other hand, IPACT, FEX-DBA and APASS do not explicitly reserve BW for the SLA packets and hence, show lesser efficiency when it comes to delivery of SLA packets. The same trend is observed when SLA packet arrival rate is 10% and 50% of the total network capacity.

Since, the SLA packets are accommodated at the expense of the ASLA packets and as a result, LASA-AuORA drops higher
number of ASLA packets than IPACT and FEX-DBA (see number of ASLA packets forwarded plots of Fig. 5 and Fig. 6). Here, we should note that the ASLA packets correspond to the on-demand applications. However, we emphasize that our priority is to successfully transmit the SLA packets. Thereafter, the ASLA packets outside SLA are served on a competitive basis. As a result, all the users might not receive enough transmission opportunity for their ASLA packets and hence, the higher drop. Finally, LASA-AuORA performs better than maxPRB-IPACT because of its end-to-end view of the network.

The notion of the end-to-end advantage of the LASA-AuORA algorithm in efficient packet delivery becomes even more clear by looking at the number of packets forwarded plots of Fig. 5 and Fig. 6. APASS is much inefficient in handling the combination of SLA and ASLA packet in the wireless network. As a result, it shows much poorer performance. The maxPRB protocol, even though it is efficient in the wireless side, lacks co-ordination with the EPON side protocols. Hence, its packet delivery efficiency becomes poorer with the increase in network load. Further, when the SLA packet percentage in the traffic is higher, maxPRB becomes inefficient in the delivery of overall packets because its biasness towards scheduling the SLA packets leads to suboptimal allocation of the wireless resources. On the EPON side, IPACT and FEX-DBA do not take any extra measures to expedite the transmission of the packets that are on the verge of crossing the delay deadlines. As a result, they induce higher packet loss as compared to LASA-AuORA algorithm.

We notice some interesting results in the delay plots of Fig. 5 and Fig. 6. We observe that the APASS-FEX delays curves are almost independent of the percentage of SLA packets in the traffic. APASS-FEX’s delay is primarily influenced by the APASS algorithm in the wireless side as a comparatively smaller number of packets are forwarded to the EPON. Therefore, the load in the EPON is never enough to really influence the EPON queueing delays. The delay for maxPRB-IPACT is lesser when the SLA packet percentage in the traffic is higher because the overall number of packets arriving to the EPON side from the LTE/5G side reduces due to the conservative approach of maxPRB. At higher loads, the delay is primarily influenced by the queueing delay of EPON. Since, the EPON load is never saturated in case of maxPRB-IPACT (with high percentage of SLA packets in the traffic mix), the delay of the delivered packets also reduces.

We further observe that at very low loads, DHAM-IPACT has lower delay as compared to LASA-AuORA. We should remember that DHAM is an optimum algorithm that maximizes network throughput, while LASA-AuORA looks into a complex mix of delay deadlines and payments resulting from SLA and ASLA packets. At very low network loads, the throughput optimal approach of DHAM proves to be better than the approach of the LASA-AuORA algorithm. However, as the LASA-AuORA algorithm tries to minimize the number of packets that cross delay deadlines, the overall delay performance of LASA-AuORA is better at higher loads. Hence, we can infer that LASA-AuORA is the most versatile protocol as compared to the benchmarks.

B. Effect of Network Load on Learning of the UEs

In this sub-section, we illustrate the efficiency of the LASA algorithm. First, we mark two UEs and vary their traffic load. We enable these two marked UEs with the capability of learning to efficiently decide on the payment per byte for their ASLA transmissions. All the unmarked UEs do not possess any learning capabilities. Hence, the unmarked UEs only pay...
the base price for the ASLA packets. Thereafter, we generate two scenarios –

- In the first scenario, the unmarked UEs transmit packets at 20% of the network load (low load condition).
- In the second scenario, the unmarked UEs transmit at 70% of the network load (high load condition).

In Fig. 7a, we observe that the learning performance is indeed dependent on the network load. Since the overall network load is much higher in Scenario 2; the marked UEs have to pay a much higher price per bit in order to transmit their ASLA packets. The higher payment ensures comparable QoS in Scenario 1 and Scenario 2, in terms of packet delay and packet transmission ratio as can be seen from Fig. 7b and Fig. 7c. However, the delay is slightly higher in Scenario 2 because the overall network load is higher. The packet transmission ratio is slightly lower in Scenario 2 for the same reason. Please note that both the marked UEs exhibit similar average performance in terms of payment, packet delay and packet transmission ratio. Hence, we can conclude from Fig. 7 that both QoS and payment-based fairness is maintained among the users. Further, we also observe that the learning-based payment is adjusted by the competing users depending upon the overall resource availability.

C. Profit Sharing Between the ONU and the OLT

In this sub-section, we illustrate the sharing of the collected credits from the UEs between the OLT and the ONUs. The ONUs simply collect the money received from the UEs and prepare the bid for their operation. The OLT allocates BW in exchange of the payment. Since, an auction procedure is being used for BW allocation, it is expected that the OLT will always end up with the major share of the money. The ONUs, on the other hand, receives slight profit as the second price VCG auction is used. The profit distribution can be clearly seen in Fig. 8. Note that the profit share of all the ONUs are statistically similar.

When the network load is low, the competition among the ONUs is less severe. The BW demand is often lower than the availability of BW slots. Since, VCG is employed, when the BW demand is lower than available BW, the ONUs receive the extra BW free of cost. BW is allocated free of cost because the discount that is given to a player is equal to the benefit it provides to the system. In this case, if the concerned ONU is absent, the BW is not utilized. Therefore, the ONU receives 100% discount. As a result, the profit share of the ONU is much higher in case of lower network loads. As the network load gradually increases, the demand exceeds the network availability and the profit of the OLT increases.

VIII. CONCLUSION

In this paper, we have proposed an end-to-end mechanism for QoS enhancement in a Wireless Optical Integrated Network that designs a medium access control layer managed intelligent spectrum access system. The scheduling in the LTE/5G network depends on the SLA of the UEs and also on the learning influenced payments that the UE is ready to make for the packets that are above SLA. The payment received in the wireless transmission is used to prepare the bids in the VCG auction that takes place in the EPON. Thus, the UEs, through their payments have an indirect control over the scheduling in the EPON. The AuORA protocol along with the LASA protocol provides SLA guarantees. The model of the AuORA protocol is in line with the supply-demand idea of Economics. The entity that wishes more BW needs to pay a higher amount to acquire it when the BW demand is more than the BW availability. Thus, the proposal ensures a fairness in user payment by taking the network load into consideration. As a future direction, the proposal can be further perfected into accommodating enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (uRLLC) and massive machine-type communication (mMTC) of 5G and also multiple classes of 6G. Further modification is possible in the auction mechanism that improves economic balance by deferring primary traffic transmissions, whenever possible. Finally, the EPON architecture can be modified to avoid any possible malicious operation in the auction mechanism by the OLT.

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