DBA Capacity Auctions to Enhance Resource Sharing across Virtual Network Operators in Multi-Tenant PONs

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Abstract: We propose an economic-robust auction mechanism for multi-tenant PON's capacity sharing that operates within the DBA process. We demonstrate that our mechanism improves PON utilization by providing economic sharing incentives across VNOs and infrastructure providers.

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1. Introduction

While current Passive optical network (PON) standards can provide data transmission capacity of tens of Gbps, in the near future, the use of more wavelengths with rates higher than 10 Gb/s could see the overall capacity increase towards hundreds of Gbps. This potential for large capacity has attracted operators to consider PON as an access network solution to serve not only residential, but also business customers and especially for interconnecting mobile 4G and 5G cells. Authors in [1] for example have estimated the 5G backhaul investment by the year 2020 to two billion dollars. The optical network industry is expected to be the key beneficiary with a dominating revenue share of 890 million. Multi-tenancy in PONs becomes crucial to enable this visions, as it reduces both capital and operating expenditures by enabling infrastructure sharing across multiple network operators. Nonetheless, the current methods for Fixed Access Network Sharing (FANS), such as bitstream unbundling, are considered limiting since they fail to offer sufficient flexibility to enable active infrastructure sharing [2]. A method for achieving the desired flexibility in FANS is the virtualization of the access network and allocation of virtual slices to multiple virtual network operators (VNOs), a concept that was initially introduced in CORD [3] and currently being standardized as cloud Central Office [4]. As stated in [5], the visualization of access networks can fundamentally transform the simple resale model of the current FANS and provide economical and operational efficiency by allowing service differentiation between VNOs.

In previous work [6] we introduced the concept of virtual Dynamic Bandwidth Allocation (vDBA), which allows sharing upstream PON channels across multiple VNOs, while each of them has in-depth control over the DBA scheduling. DBA plays the most significant role in the PONs upstream resource allocation and shapes the service qualities associated with it. Hence, its virtualization is key to make the PON a truly multi-service and multi-tenant access infrastructure. This enables providing customized and guaranteed quality of service, e.g. in terms of latency, jitter, and capacity, to multiple applications across operators sharing the same physical infrastructure.

However, one of the main issues in multi-service, multi-tenant PONs is that the diversity of customers, services and application running on it, together with the bursty nature of the traffic can lead to traffic demands that can severely fluctuate across different VNOs. Thus sharing un-used capacity across VNOs is crucial for achieving high network efficiency. However, without any incentives, VNOs have no interest in re-distributing their unused capacity to other VNOs unless a business case guarantees a return on their "generosity".

In this paper, we propose a solution to this problem which makes use of a fast one-time auction during DBA scheduling. These auctions only require one transaction between sellers and buyers, thus, as explained in the next section, they can run as part of the DBA algorithm, without requiring any additional communication between VNOs. Finally, our solution is economic-robust as we address the issue of potential market manipulation: by adopting the Vickrey-Clarke-Groves (VCG) auction type, VNOs cannot gain any benefit by artificially manipulating their valuations.

2. Auction Model

Auctions are well-investigated mechanisms for spectrum sharing in wireless telecommunication, both by academia and industry. The Federal Communications Commission (FCC), for example, uses auctions for static, long-term spectrum allocation among large operators. The drawback of static sharing is, however, the exhaustion of available spectrum, leading to extreme under-utilization [7], and the difficulty for newer and smaller network operators to enter the market and promote competition. These shortcomings motivated the research community to move towards dynamic spectrum trading, allowing primary network operators to sell their vacant spectrum for monetary gains, and secondary users to purchase the available licensed spectrum on-demand. As PONs move towards multi-tenancy, we will see a similar issue arising. As multiple VNOs, each one running their own DBA algorithm, share the same PON channels [6], they have no incentive in requesting, for every frame, anything less than their assured bandwidth, as any unclaimed capacity will be reallocated the scheduler to their competitors. The auction we propose aims at setting a framework for trading capacity on a frame-by-frame basis. It should be noted that these can be carried out exchanging capacity credits, which can then be settled with monetary transactions on a longer time-scale, for example on a monthly basis. In auctions,

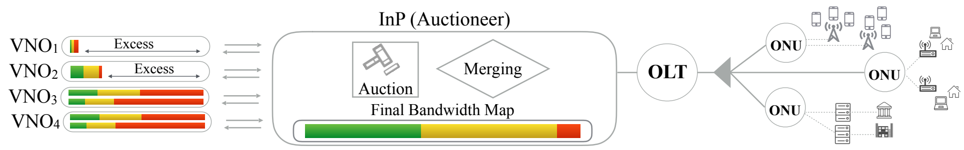


Fig. 1: Our proposed model for DBA capacity auctions in multi-tenant PONs.

economic-robustness is defined by the following properties: truthfulness or incentive compatibility (IC), individual rationality (IR), and budget balance (BB) [7], which are explained below. In the context of the multi-tenant PON, the utility of a VNO as well the InP is the amount of their payoff from engaging in the auction whether from selling or buying transmission opportunities. Taking the definition of utility into account, IR means guaranteeing always positive utility for all the VNOs and BB implies a non-negative utility for the InP. IC, on the other hand, will be satisfied when the auction is designed in a way that for all the traders, reporting the true value of the goods is the dominant strategy, i.e., no VNO can achieve higher utility by reporting an untruthful value. Auction theory and mechanism design have been studied for decades. An outcome of these studies is VickreyClarkeGroves (VCG) auction, that is known to be economic-robust while maximizing the overall utility of the system [8]. It should be noted that the Impossibility Theorem [9] states that no double auction can simultaneously achieve all three economic properties described above while maximizing auction efficiency. Thus, to achieve economic robustness, a degree of efficiency loss is inevitable.

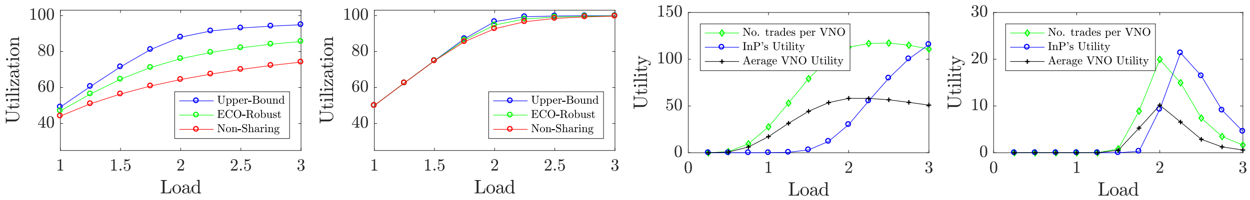
Fig. 1 illustrates the concept of multi-tenant PON in which VNOs can trade (sell or buy) excess upstream transmission opportunities at the highest granularity (i.e., 16-byte word). In Fig. 1 the VNOs' requested bandwidth is depicted in different colors each representing a QoS class, i.e., traffic containers (T-CONTs). The InP's controller hosts the auction mechanism which determines the auctioned capacity, while the merging engine generates the resulting bandwidth map. In every frame (125μs), each VNO will announce its demand for the upstream transmission opportunity in the form of a number of frame units (FUs) accompanied by a value representing its average per-FU valuation. The InP will receive the two values and then compare them simultaneously using a matching algorithm to buy $\Sigma = Min(Supply, Demand)$ number of the FUs from the cheapest VNOs and sell them to the highest bidders. Then, our proposed mechanism will determine the price to pay for FUs. The auction consists of a set of $M = \{m_1, m_2, ..., m_i\}$ seller VNOs and a set of $N = \{n_1, n_2, ..., n_j\}$ buyer VNOs and the auctioneer (InP).

$$VCG\ Price = \Lambda^{N-j} - (\Lambda^N - \lambda^j) \qquad (1) \qquad Winner's\ Price = Max(VCG\ Price, Base\ Price) \qquad (2)$$

In Eq. (1) Λ^N is the total revenue from all the winner buyers, Λ^{N-j} is the total revenue with VNO_j not present in the auction and λ^j the revenue solely generated by VNO_j. The idea behind Eq. (1) is to charge the winner VNO by the amount of harm it causes to the market by winning the items. Eq. (2) applies the Base Price as the minimum payment per FU to ensure budget balance. The proposed mechanism buys the items from the sellers for a fixed *Base Price* and sells them to the buyers with the VCG price. The per-FU value of VNOs represents the probability of utilizing the FU (thus in the range [0,1]). We have set a fixed value for the *Base Price* to 0.5: this bounds the number of eligible traders to the sellers with a value lower and buyers with a value higher than 0.5. In this way, we can guarantee that none of the sellers, buyers or the InP will regret participating in the auction due to a negative utility. Furthermore, any eligible seller will receive a fixed per-FU price of 0.5 regardless of its reported value, eliminating the possibility of market manipulation. This approach follows the idea behind McAfee's mechanism [10], that uses trade reduction to achieve truthfulness. Our choice of the specific 0.5 value is to remove an equal number of sellers and buyers from the market.

3. Results

To examine the impacts of different approaches toward sharing the PON capacity, we compare three mechanisms:
1. The "Non-sharing" mechanism in which each VNO gets its fixed share of the frame regardless of the demand;
2. The "Upper-Bound" mechanism in which the items from the cheapest sellers are sold to the highest offers for the reported values with a naive assumption of truthfulness (not economic-robust);



(a) Unbalanced Load (b) Balanced Load (c) Utility-Unbalanced Load (d) Utility-Balanced Load

Fig. 2: Simulation results of our DBA auctions, showing how the auction mechanism increases PON utilization.

3. Our proposed "Economic-Robust Sharing" mechanism that facilitates the sharing through buying the items from the sellers for a fixed price of 0.5 and selling them to the buyers to the VCG price.

We have simulated a multi-tenant PON market considering a10-Gbps symmetrical PON (i.e., XGS-PON). The simulation duration is 6 seconds, which allows us to average our results over 48,000 frames, each of 125 μs duration. The PON is shared amongst 10 VNOs, each serving 10 Optical network units (ONUs). Although not reported, we have repeated the same simulations for different numbers of ONUs and VNOs, obtained similar results.

Our results are reported in Fig 2, comparing the three sharing mechanisms described above. Fig2.a shows the network utilization for an unbalanced load scenario (i.e., the mean of the traffic generated by the ONUs is assigned according to a random uniform distribution), confirms that our proposed economic-robust mechanism outperforms the Non-sharing by achieving higher utilization across all offered loads. The Upper-Bound scenario reflects the case that with no trade reduction and, as a result, it increases the number of trades, leading to higher utilization. Its important to note though that the upper-bound is idealistic since without incentivizing VNOs to report their truthful value, they will likely manipulate their bids to achieve higher utility: the buyer VNOs shading their bids, and the sellers reporting higher untruthful values. This leads to a higher price per item from the sellers and lower offer per item from buyers leading to a natural reduction of trades. However, our results do not account for the manipulative bidding behavior of the VNOs. In Fig 2.b we report, for completeness, the scenario with the balanced load across the ONUs, although this is less realistic. As expected, although the trend is confirmed, the difference between the three mechanisms is much less remarked, as the number and value of the trades are far less when VNOs all have similar traffic. Fig 2.c compares, for the unbalanced load scenario, the average VNOs' and InP's utility against the average number of trades conducted during each frame using the proposed mechanism. We define the VNOs' utility as the difference between their trading price and their valuation for the FU, .i.e. this determines how close is their final payment to their perceived value. The InP's utility is the difference between the trading price of the seller and buyer VNOs, i.e., this reflects the price gap occurred due to the supply and demand ratio. Both Fig 2.c and Fig 2.d show that as we move to the right along the X-axis, the ratio of the demand to supply increases and, as a natural reaction, the market adapts by raising the price. As the number of trades increases, VNOs and the InP gain more utility. Once the overloading ratio exceeds the factor of 2, the VNOs become more demanding. At the same time, the supply declines and leads to fewer trades and eventually almost no trade when it reaches saturation as all the VNOs are asking for more than their negotiated share. By design, while the supply is higher than the demand the trading price is equal to the base price thus the utility of the InP remains zero. Once the demand grows over the supply, the price rises and the InP's utility starts to grow. The InP's utility is at its highest when the number of trades is maximum, and the average price of an FU is high.

To conclude, our work has shown that economic sharing incentives are indispensable in fully virtualized multi-tenant PONs to increase the overall utilization. Our proposed market mechanism significantly improves the utilization of the PON compared to the Non-sharing scenario while achieving the desired economic robustness.

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