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Ph.D. Dissertation

Techno-economics of Optical Access Network Sharing

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22nd July 2020

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Declaration

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Nima Afraz, 22nd July 2020

This dissertation is dedicated to Omid Kokabee[a] *optical physicist, a prisoner of conscience, and the Scholars at Risk*[b] *worldwide.*

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[a] Dr. Kokabee is the recipient of the 2014 APS Andrei Sakharov Prize for his courage in refusing to use his physics knowledge to work on projects that he deemed harmful to humanity, in the face of extreme physical and psychological pressure, while he was fighting cancer in prison.

[b] https://www.scholarsatrisk.org

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Summary

Several parallel trends, including the growing number of Internet reliant devices/services, increasing Internet penetration rates, and the continuing popularity of bandwidth-hungry multimedia content contribute to the exponential surge of Internet traffic. The combination of these trends could imply a considerable increase in network infrastructure investment for the telecom and broadband operators. In addition, the high cost of initial investment could escalate the market barriers to entry for the innovative service providers incapable of deploying their own network infrastructure. In this dissertation, we explore if and how enabling optical access network sharing could cultivate new network ownership and business models that simultaneously keep the end-user subscription fees low and facilitate the market entry for the smaller service providers. We aim to identify and address the technological and economic barriers of optical access network sharing. The broad scope of this dissertation concerns the inter-operator sharing of optical access networks which connect the end-users to the operators' network in the last-mile. The access segment of the communications network is recognized to be the most costly due to its deployment scale. Therefore, a reduction in cost in the access will have a multi-fold impact on the overall capital expenditure for network deployments. The dissertation focuses in particular on Passive Optical Networks (PONs) as the most widespread type of optical access networks.

The central argument of the present research is that network infrastructure/resource sharing has the potential to reduce the capital and operational expenditure of the network operators. This will allow for more competition as the market entrance cost decreases.

We first address the lack of tenant operators' adequate control over the shared resources in a multi-tenant PON as a technological barrier. We provide a solution to strengthen the network operators' control over their share of the network in a multi-tenant PON. This is made possible by allowing the operators to schedule the transmission over the network using tailored algorithms to meet their requirements (e.g., latency and throughput). The dissertation argues

that providing a virtual (software) instance of the Dynamic Bandwidth Allocation (DBA) algorithm as opposed to the inflexible hardware implementation first, enables the coexistence of various services on the PON and second, improves the overall utilization of the network capacity.

While the virtualization of the DBA removes the technical barrier for the inter-operator resource sharing, it does not come with a natural incentive for the operators to share their resources with competitors. Therefore we tackle the lack of incentive for sharing excess network capacity in PONs by providing monetary compensation in return for sharing. We model the multi-tenant optical access network with multiple coexisting operators as a market where they can exchange their excess capacity. We propose a sealed-bid multi-item double auction to enable capacity trading between the network operators. Through mathematical proof and market simulation/visualization, we prove that the proposed auction mechanism meets the essential requirements for an economic robust market mechanism (e.g., incentive compatibility, individual rationality, and budget balance). This provides trusted market conduct in the presence of a central authority (e.g., the public infrastructure provider) that all the operators trust.

The shift in the market ownership models motivated us to explore an alternative scenario where no central entity can be trusted to provide fair and impartial infrastructure management. Therefore, we argue that the blockchain technology can be exploited to hold the market in a distributed fashion as an alternative to centralized control. To analyze the feasibility of such a distributed market, we developed smart contracts that implement an auction algorithm capable of allocating the resources to the participants without a central trusted market mediator. We use the open-source framework Hyperledger Fabric to develop the blockchain application. The nodes of the blockchain network are then distributed across multiple cloud-hosted virtual machine instances to allow more realistic and precise experimentation. We use common metrics such a transaction latency and throughput to evaluate the performance of the designed marketplace application. Furthermore, we study the computing resources required to run the blockchain application.

Acknowledgments

As I wrap up this dissertation in quarantine, the entire world is battling a pandemic and we are urged to *"stay safe and stay apart"*. The past few weeks of seclusion have made me appreciate more than ever the people who generously offered their companionship throughout these years.

This research would not have been possible if it was not for the trust, guidance and support of Prof. Marco Ruffini even at times that he would find me napping on my desk. I have also profited greatly from conversations with Prof. Hamed Ahmadi, Dr. Irene Macaluso, Dr. Harun Siljak, Prof. Luiz Da Silva, and Prof. Linda Doyle.

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1 Introduction

Introduction

"It is impossible to travel faster than the speed of light, and certainly not desirable,
as one's hat keeps blowing off."

—Woody Allen

This dissertation studies the technological and economic implications and requirements of optical network sharing. We propose a solution to enable fine-grained and dynamic inter-operator sharing of the resources using virtualization technology. We show that a carefully designed resource sharing market mechanism can provide sharing incentives for competing operators and enhance the network utilization and value generation. Furthermore, we show how a blockchain-based distributed marketplace for network resources could alleviate the trust issues in conventionally centralized markets. Figure 1.1 depicts the scope of the dissertation.

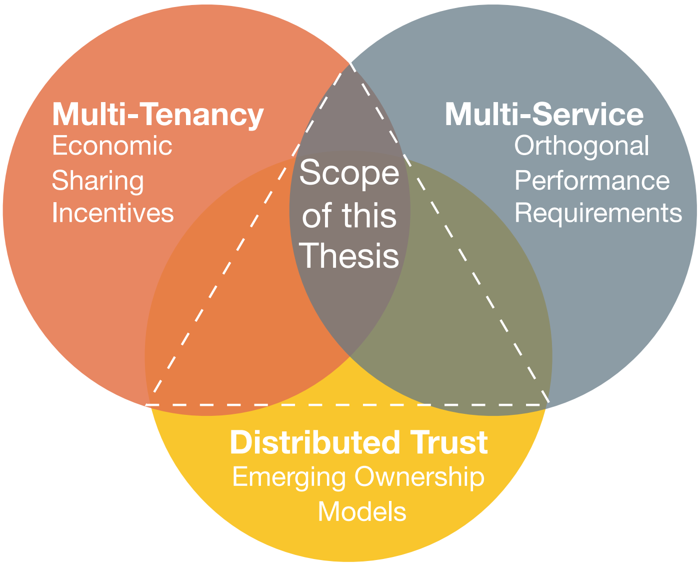

Figure 1.1: The Scope of this Dissertation

1.1 Overview and Motivation

The accelerating changes in the average Internet users' behavior have caused a surge in high-throughput traffic classes such as online video streaming that causes periodical peak demands, i.e., sudden surges in bandwidth demand. Under these conditions, the conventional over-provisioning of the bandwidth to accommodate the peak demand is very costly and is not economically justifiable. According to Cisco [2] peak-hour (the busiest 60 minute period in a day) Internet traffic is growing faster than the average Internet traffic. Peak-hour Internet traffic increased 51 percent in 2016, compared to 32-percent growth in average traffic. The communications network operators are seeking cost-effective ways to accommodate new services and meet the users' accelerating demand for network capacity. Meanwhile, the traditional sole ownership of the network remains open as an important challenge since it becomes highly cost-inefficient as more expensive equipment and transmission medium are to be deployed. Thus, new joint ownership/operation models become more appealing to the operators as they can considerably increase cost-efficiency.

Sharing the network reduces the Capital Expenditure (CapEx) by splitting the infrastructure investment as well as the Operating Expenditure (OpEx) through the economy of scale, for the operators. Therefore, lower *"cost per bit"*, i.e., the delivery cost of a bit to a user over the network, can be achieved. As a result, lower *cost per bit* can allow wider network deployments in under-served communities, and therefore, exponential growth in Internet penetration rate can be expected. This growth will bridge the digital divide bringing affordable access networks to the areas (e.g., remote rural areas) that would not have been served in conventional sole-ownership network deployment (unless if heavily subsidized by public funds). Furthermore, with proper regulations in place, new network ownership/operation models can emerge that will impact competition by alleviating network entrance barriers. In other words, eliminating the prohibitive preliminary investment costs to enter the network as an operator facilitates innovation. The advantages of network sharing are evident to the extent that in majority of countries some forms of network sharing have been mandated by the authorities [3]. In the context of optical access networks, cost reduction will be possible by increasing infrastructure utilization. One approach to sharing the infrastructure is the passive sharing in which the operators share the site and the passive equipment. The second approach that will be our primary focus in this dissertation is active infrastructure sharing (further discussed in chapter 3) that will enable improvements in network utilization by more fine-grained sharing models. Coarse-grained active network sharing already exists in the optical access domain. For instance, sharing a Passive Optical Network (PON) by dedicating an entire wavelength to each operator is possible using the currently available technologies. However, such coarse-grained sharing models will impose boundaries on the extent at which sharing can be achieved. It is only with fine-grained active network sharing that the advantages of network sharing can reach their full potential.

Fixed network sharing has been also addressed by standardization bodies. The BroadBand Forum (BBF) is a non-profit industry consortium working towards defining and developing broadband network specifications. In [4] the BBF defines the stakeholders involved in the fixed access network sharing: first, the Infrastructure Provider (InP), an organization that acts as a wholesaler of network infrastructure and maintains the physical network resources; second, the Virtual Network Operator (VNO), that leases resources from the InP and utilizes those resources to provide services to end-users. The same report also provides guidelines for sharing of data and control with a network sharing system, that interfaces on the northbound side with VNO management systems, and interfaces on the southbound side with network equipment and systems. Infrastructure growth, energy efficiency, lower time to market, and time to revenue are some of the drivers that the BBF promotes by their new collaborative sharing model called Fixed Access Network Sharing (FANS) (TR-370 [5]). They study the alternative sharing models to *bitstream* (i.e., the simple resale of the broadband service) stating that the pre-negotiation required to make any changes in bitstream makes it an unfit model for future flexibility-seeking applications.

One of the enabler technologies for network sharing is virtualization of network functions that can facilitate multi-tenant network scenarios by providing VNOs with immediate access to network functions without any intervention from the InP. Therefore, relieving VNOs from both owning and operating the physical network infrastructure while benefiting from a flexible and customizable virtual infrastructure. The concept of multi-tenancy would be more attractive to the network operators when they could have adequate control over the infrastructure to satisfy the diverse requirements of their users. Currently, this can be achieved thanks to the virtualization technologies introduced to telecommunication networks empowered by software defined networking, and its main features of control plane centralization and network programmability. Virtualization can provide heterogeneous networks with on-demand customizability and empower dynamic management of resources [6].

In the context of PONs, which are being considered as one of the most promising access network options for a wide range of services from residential Fiber-to-the-Home (FTTH) to mobile backhaul and fronthaul [7], virtualization of the Optical Line Terminal (OLT) and ONU can bring considerable flexibility to the PON. The OLT is responsible for the management of the ONUs, framing of the data, and scheduling the down/upstream traffic in a time-division multiplexing (TDM) manner. In a shared PON, the tenant operators may offer different services with diverse requirements where the absence of adequate control over the OLT's features can be a significant obstacle for the realization of the multi-tenant networks. For instance, previous research [8] has established that new services such as mobile fronthaul if deployed on current PONs cannot unlock the full potential of the Dynamic Bandwidth Allocation (DBA). This is due to the stringent latency requirements of these services that do not allow them to tolerate the time-consuming status report and grant process of the conventional DBAs. In other words, these new services can only use the current PONs, with no change required, through static bandwidth allocation (using fixed periodical grants) to circumvent the latency caused by the DBA [9]. Alternatively, new DBA methods (e.g., low latency DBA [10]) have been developed to allow new services to enjoy the dynamic nature of bandwidth allocation in PONs. However, these new DBAs require altering the OLT's software/hardware. Consequently, in a scenario where heterogeneous service providers are supposed to share the same PON physical infrastructure, one would have to settle for the other operators' benefit (i.e., to use their desired version of the DBA) since the DBA is hard-coded into the OLT's hardware and is not easily customizable. Thus, virtualizing the DBA mechanism can enable the network operators to easily implement their own version of the bandwidth allocation and utilize the full potential of the PON. In this dissertation, we introduce a multi-tenant PON architecture enabling customized DBA implementation for the tenant VNOs. The DBA algorithm in a PON is responsible for generating a Bandwidth Map (BMap) dictating the upstream transmission opportunities for each ONU per each frame. The DBA has to generate this BMap for every frame, every 125 microseconds.

In the multi-tenant PON model, each VNO operates a virtual instance of their preferred DBA that will generate a Virtual Bandwidth Map (vBMap) for its share of the frame. Then the merging and final layout of the BMap is facilitated by the merging engine. However, in a scenario where each VNO has a dedicated share of the bandwidth according to its Service

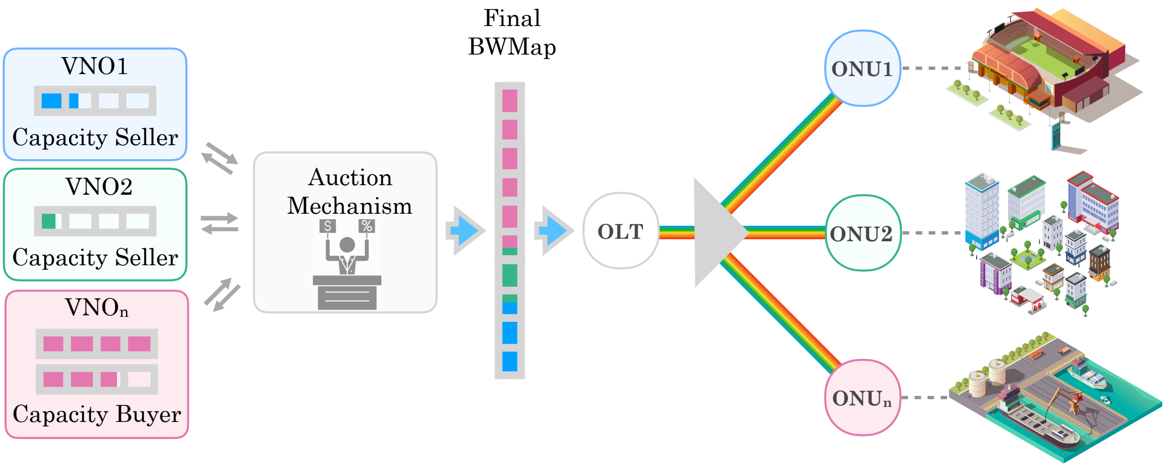

Figure 1.2: Multi-Tenant PON Sharing Market

Level Agreement (SLA) with the InP, there is a high chance that some of the VNOs will have excess unused bandwidth. This is due to the bursty nature of data traffic. This will lead to a point where a considerable percentage of the resources will go to waste when the operators are not able to share their excess capacity with others. Nevertheless, it should be taken into account that these network operators possibly are competing to gain more market share by increasing their customer base. Hence, without any incentives, VNOs will have no interest in re-distributing their unused capacity to other VNOs unless a business case guarantees a return on their *generosity*. To address this obstacle, in chapter 4 we introduce a marketplace (depicted in Figure 1.2), where the operators can receive monetary compensation in return for sharing their excess resources (upstream PON transmission capacity). We make use of an auction mechanism to ensure sharing incentives and satisfaction of the typical economic market properties, including truthfulness. However, while the auction-based approach provides high overall resource utilization, it does so under the assumption of an open-access architecture, where a fully trusted, independent central authority (e.g., the InP) is in charge of operating the market (i.e., bookkeeping, conducting the auction, settlements, etc.). This assumption may not always be valid for today's network ownership models, where often the incumbent operator owning the physical infrastructure is also a competing VNO. We have thus tackled the more general problem of untrusted InP through the use of distributed consensus mechanisms (e.g., blockchain-based smart contracts), which do not rely on a central entity to reach a collective decision.

1.2 Research Questions

- What are the motivations and implications for optical access network sharing?
- How to meet the technical requirements to enable fine-grained and dynamic optical access network sharing?
- Could monetization of excess resources incentivize the operators to share their excess resources with competitors?
- Could an economic robust double auction mechanism provide market participation incentives for inter-operator network sharing?
- Could the blockchain technology be leveraged to address the lack of trust in centralized network sharing markets?

1.3 Contributions

In the study of the technological and economic enablers of optical network sharing the following primary contributions are made:

1.3.1 True PON Multi-Tenancy Enabled by DBA Virtualization

- Enabling true and flexible multi-tenant PON architecture by providing the network operators with more control over their share of the resources. This is achieved by providing a virtual hence customizable instance of the DBA as opposed to the hard-coded DBAs in conventional PON architecture.

1.3.2 Designing a Market Model and Auction Mechanism for Multi-Tenant PONs

- Designing a market model for the multi-tenant PONs that incentivizes the tenants to willingly participate in resource sharing to achieve a common objective, which is reducing the infrastructure costs and facilitate the widespread network coverage. In the proposed market model, the network tenants are compensated monetarily in return for sharing their idle share of the network with others. The model depends on a central trusted entity that is responsible for book-keeping and processing the market.

- Proposing a new sealed-bid, multi-item, *double auction* mechanism to efficiently allocate the resources while maximizing the social welfare of the entire market. We have proven that our proposed algorithm is compatible with the VNOs' incentives and guarantees a positive budget for the InP. These achievements are reached while the mechanism adds no additional communication overhead to the system due to its single rounded (sealed-bid) nature.
- Proposing a trade reduction mechanism for the double auction that scarifies fewer trades to achieve the crucial economic properties. This significantly increases the allocative efficiency compared to the state-of-the-art double auctions.

1.3.3 Distributed Network Sharing Market Ecosystem

- Exploiting the blockchain technology to design a distributed market model for network sharing. Using smart contracts we implemented a distributed auction mechanism that does not rely on a central entity to conduct the auction.
- Implementing two use cases using the proposed distributed market including Multi-Tenant PON capacity sharing and Fifth Generation (5G) network slice brokering.
- Evaluating the performance of the proposed use cases of the distributed market model using pragmatic cloud-based deployment of the blockchain solution using Hyperledger Fabric.

1.4 Structure

The Structure of this dissertation is as follows:

- In chapter 2 we give an introduction along with a state-of-the-art review of the underlying concepts addressed in this dissertation. It begins with an introduction to PONs (section 2.1) as the main access network solution under the study in this dissertation and its crucial DBA function (subsection 2.1.1). In section 2.2 we introduce network sharing as the main scope of this dissertation while elaborating on market players' aggressive competition policies and the emerging network ownership models that are born out of such market dynamics. In section 2.3, we provide some background for network virtualization and related technologies while showing how they can facilitate network sharing. A brief literature review on the auction theory and in particular double auctions is provided in section 2.4. Finally, in section 2.5, we provide the necessary background for blockchain and smart contract technology with a focus on their application in communications and distributed market mechanisms.

- In chapter 3 we address the technological barrier of multi-service optical access sharing by introducing a new architecture for multi-tenant PONs, which enables customized resource allocation for the tenant operators.
- In chapter 4 we model the multi-tenant PON network as a market (section 4.1) while introducing the roles of the agents involved in the market. We further propose an auction mechanism (section 4.2) to enable bilateral trade in the multi-tenant PON market. Theoretical proofs for the satisfaction of the economic properties and the analysis of the allocative efficiency of the proposed mechanisms are also provided in this chapter.
- In chapter 5, a distributed market mechanism based on permissioned blockchain technology, is introduced. The proposed distributed mechanism implemented using the smart contract technology is then applied to two different scenarios, including the multi-tenant PON and 5G slicing. The cloud-based implementation and deployment of the market are included in this chapter. The blockchain-based solution is evaluated in terms of transaction throughput, latency, and required additional computational resources.
- Concluding remarks are given in chapter 6 along with a discussion of limitations and future work.

1.5 Dissemination

1.5.1 Peer-Reviewed

1. **N. Afraz**, F. Slyne *et al.*, “Evolution of Access Network Sharing and Its Role in 5G Networks”, *Applied Sciences - Special Issue on Optical Network Evolution Towards 5G*, vol. 9, no. 21, p. 4566, Oct 2019.
2. A. Elrasad, **N. Afraz**, M. Ruffini , “Virtual Dynamic Bandwidth Allocation Enabling True PON Multi-Tenancy”, in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, March 2017, pp. 1–3.

3. **<u>N. Afraz</u>**, F. Slyne, M. Ruffini, “Full PON Virtulisation Supporting Multi-Tenancy Beyond 5G [Invited]”, in *OSA Advanced Photonics Congress (AP) 2019*, Optical Society of America, 2019, p. NeT2D.2.
4. M. Ruffini, A. Ahmad, S. Zeb, **<u>N. Afraz</u>**, and F. Slyne, “The Virtual DBA: Virtualizing Passive Optical Networks to Enable Multi-Service Operation in True Multi-Tenant Environments”, *Journal of Optical Communications and Networking (JOCN)*, Jan. 2020.
5. **<u>N. Afraz</u>** and M. Ruffini, “A Sharing Platform for Multi-Tenant PONs”, *Journal of Lightwave Technology (JLT)*, vol. 36, no. 23, pp. 5413–5423, Dec 2018.
6. **<u>N. Afraz</u>** and M. Ruffini, “A Marketplace for Real-Time Virtual PON Sharing”, in *2018 Asia Communications and Photonics Conference (ACP)*, Oct 2018, pp. 1–3.
7. **<u>N. Afraz</u>**, A. Elrasad, M. Ruffini, “DBA Capacity Auctions to Enhance Resource Sharing Across Virtual Network Operators in Multi-Tenant PONs”, in *2018 Optical Fiber Communications Conference and Exposition (OFC)*, March 2018.
8. **<u>N. Afraz</u>**, A. Elrasad, H. Ahmadi, M. Ruffini, “Inter-Operator Dynamic Capacity Sharing for Multi-Tenant Virtualized PON”, in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Oct 2017, pp. 1–6.
9. **<u>N. Afraz</u>** and M. Ruffini, “A Distributed Bilateral Resource Market Mechanism for Future Telecommunications Networks”, in *2019 IEEE Global Communications Conference (GLOBECOM)*, December 2019.
10. **<u>N. Afraz</u>**. and M. Ruffini, “5G network slice brokering: A Distributed Blockchain-based Market”, in *2020 European Conference on Networks and Communications (EuCNC): Network Softwarisation (NET) (EuCNC2020 - NET)*, Dubrovnik, Croatia, Jun. 2020 [under review].

The following works are the outcome of collaboration with other researchers in areas loosely related to this dissertation but not described in the dissertation:

11. A. Khatoon, **<u>N. Afraz</u>**, “Approaches to Adopt Blockchain Technology for the Internet of Things”, in IEEE Technology and Society Magazine [under review].
12. M. Hajizadeh, **<u>N. Afraz</u>**, M. Ruffini, and T. Bauschert, “Collaborative Cyber Attack Defense in SDN Networks using Blockchain Technology”, in *2nd International Workshop on Cyber-Security Threats, Trust and Privacy management in Software-defined*

and Virtualized Infrastructures (SecSoft 2020), Ghent, Belgium, Jul. 2020.

1.5.2 Patent

1. M. Ruffini, A. Elrasad, **N. Afraz**, “System and Method for Dynamic Bandwidth Assignment (DBA) Virtualization in a Multi-Tenant Passive Optical Network”, Patent WO/2018/167 318, Sep., 2018.

1.5.3 Tutorial Talks

1. H. Ahmadi, I. Macaluso, M. Ruffini, **N. Afraz**, “Blockchain Technology and Smart Contracts in 5G and Beyond Networks [Delivered]”, 2019, European Conferences on Networks and Communications (EUCNC).
2. H. Ahmadi, I. Macaluso, M. Ruffini, **N. Afraz**, “Blockchain Technology and Smart Contracts in 5G and Beyond Networks [Accepted and to be Delivered]”, 2020, IEEE International Conference on Communications (ICC).

1.5.4 Open-Source Community Engagement

I am currently the chairperson in the SLA subcommittee in the Hyperledger Telecom Special Interest Group (hosted by the Linux Foundation) that is focused on technical and business-level conversations about appropriate use cases for blockchain technology in the Telecom industry. The following solution brief was a publication resulting from this collaboration:

- **N. Afraz**, V. Chaudhary *et al.*, “Optimizing Wholesale Intercarrier Settlement with Hyperledger Fabric Blockchain”, *Solution Brief.* Telecom Special Interest Group, 2019.

2 Background

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Background

"Information is power. But like all power, there are those who want to keep it for themselves."

—Aaron Swartz

This chapter provides the background on the broader context of the problem addressed by this dissertation. It covers a brief history of the standardization efforts as well as a review of the literature in the research domain relevant to this dissertation, including Passive Optical Networks (PONs), network sharing, virtualization, and blockchain technology. While reviewing the previous research, we keep in mind the question "*What are the motivations and implications for optical access network sharing?*"

In section 2.1, we briefly introduce PONs that form the main scope of this dissertation. In subsection 2.1.1 we provide a brief review of the Dynamic Bandwidth Allocation (DBA) algorithms. Section 2.2 introduces the main theme of this dissertation that is network sharing and investigates the technological and economic challenges associated with it. In section 2.3, we review network virtualization and Software Defined Networking (SDN) as the technological enablers of network sharing. Section 2.4 lays out the theoretical dimension of game-theoretical approaches towards resource sharing problems in telecommunications with a focus on auction mechanisms. Finally, section 2.5 provides an introduction to blockchain technology accompanied by a brief overview of its solution to the trust-less business ecosystems.

2.1 Passive Optical Network (PON)

Access networks are the most expensive part of telecommunication networks due to the scale of their deployment (in terms of termination points and users) and the massive number of network elements they require. Consequently, intensive research has been carried out to address different aspects of this vital part of the telecommunication networks. For over a decade, Digital Subscriber Line (DSL) over copper dominated the fixed access market by providing point-to-point wired access to support each subscriber with up to 24 Mbit/s downstream using its most popular version ADSL2+ [11]. Fast Access to Subscriber Terminals (G.Fast) [12] is another protocol based on DSL designed for local loops shorter than 500 meters 100 Mbit/s and 1 Gbit/s. Even though G.Fast promises sufficient bandwidths, considering the short reach and the small number of subscribers that the technology can support, substantial investment is required to deploy it. Since, these access technologies entail a considerable number of active network elements such as routers, switches, etc. and on the other hand, they are unable to fulfill subscribers' growing thirst for bandwidth. Whereas, optical networks are becoming more and more popular in core and access networks thanks to the vast bandwidth capability they provide compared to their counterparts.

PONs are a series of fixed access network technologies that offer numerous advantages when deployed in Fiber-to-the-x (FTTx) scenarios. The advantages include a point to multi-point architecture, high-quality triple play service capabilities for data, voice and video, high-speed Internet access, and other services in a cost-effective manner [13].

PON's bandwidth management technique in downstream is similar to a simple broadcast-and-select network which broadcasts data to all Optical Network Units (ONUs), and then the relevant ONU would be able to access its requested data. On the other hand, in the upstream direction the ONUs send data towards the same Optical Line Terminal (OLT). The Dynamic Bandwidth Allocation (DBA) is responsible for making sure that no collision will occur, and the upstream bandwidth will be fairly shared among the ONUs. Furthermore, the bandwidth allocation process should respect the Service Level Agreement (SLA) and Quality of Service (QoS).

The point to multi-point nature of PON enables the support of numerous users up to 1024 ONUs, and 125 kilometers reach recently demonstrated [14]. The available capacity reaches up to 10 Gbps symmetric rates per channel, with up to 8 channels in NG-PON2, with standardization efforts aiming at 25 Gbps per channel and research results showing rates of 100 Gbps. These characteristics of PON makes it a suitable candidate for being used as shared infrastructure. The long reach, power budget, and high capacity of PON makes it an excellent infrastructure option for different environments from remote rural areas, as one PON can potentially support the entire traffic of a village, to the dense traffic in the city center of a big city. However, sharing the PON among multiple operators with potential service diversity demands a reliable QoS scheme to guarantee sustainable service delivery to the end-users, i.e., sharing shall not prevent the operators from implementing their QoS scheme to satisfy diverse service-dependent requirements. Failing to provide this service differentiation in a PON can break the chain of end-to-end QoS and interfere with the traffic engineering capability of the operators. For example, Ultra-Reliable Low-Latency Communication (URLLC) services offered by 5G are only feasible if the mobile operators can directly tune the scheduling mechanisms of the network and implement optimization techniques required for their proper functioning.

Two standardization bodies including Institute of Electrical and Electronics Engineers (IEEE) and International Telecommunication Union (ITU), are in parallel developing standards for PONs. The two standards are known, respectively as Ethernet Passive Optical Network (EPON) and Gigabit Passive Optical Network (GPON). The idea of EPON was developed by the IEEE 802.3 study group called Ethernet in the First Mile (EFM) in November 2000 [15]. The group was to extend Ethernet into the subscriber access area. Ethernet over point-to-multipoint (P2MP) fiber (also known as EPON) was one of the focus areas of this group. The efforts of this group was reflected in IEEE 802.3ah-2004 [16] which were later included in the overall standard IEEE 802.3-2008 [17], 2012 [18] and the most recent amendment to it IEEE P802.3ca 100G-EPON [19].

Gigabit-capable PON is a QoS-enabled variant of PONs that has been standardized by the ITU in the G-series recommendations. GPON employs an embedded QoS technique by defining logical queues called Transmission Containers (T-CONTs) for different service types with higher service frequency for delay-sensitive application and more significant transmission opportunities for bandwidth-hungry applications. GPON is defined as ITU-T G.984 [20] series of recommendations. More recent versions of this standard are known as 10 Gigabit PON (XG-PON), and Next-Generation Passive Optical Network 2 (NG-PON2) justified in ITU-T G.987 [21] and ITU-T G.989 [22], respectively.

XG-PON and NG-PON2 are based on GPON and inherit most of its features, including framing and management techniques with improvements in bit-rate and coverage. A standard

GPON system can typically accommodate 64 users at a maximum distance of 20km (OLT to ONT) with downstream/upstream rate of 2.5/1.25 Gbit/s while XG-PON operate at 10/2.5 Gbit/s bandwidth and can increase the support to 128 users or increase the distance at 60km but not simultaneously. NG-PON2 takes the bandwidth to up to 40 Gbit/s symmetrically for both downstream and upstream thanks to the TWDM technique.

2.1.1 Dynamic Bandwidth Allocation (DBA)

The best known DBA algorithms for EPON and GPON are IPACT [23] and GIANT [24], respectively. ITU considered the addition of the DBA to its B-PON standards in recommendation G.983.4 [25]. This recommendation specifies the requirements to equip broadband optical access systems defined in ITU-T Rec.G.983.1 [26] with DBA functionality where the concept of T-CONT is defined, and the types are discussed in detail.

ITU-T G.989.3 [27], 40-Gigabit-capable passive optical networks (NG-PON2): Transmission Convergence Layer Specification introduces the guidelines and principles for the upstream and downstream resource allocation along with the quality of service capabilities of the NG-PON2. This recommendation presents a more mature and detailed description of the DBA in general and concise mathematics to formulate the different types of bandwidth specified in the algorithm, such as guaranteed, non-assured, and best-effort. Furthermore, an extended bandwidth assignment model is introduced and demonstrated via a realizable architecture. The reference model imposes a strict priority hierarchy for different forms of assigned bandwidth. This hierarchy is the main building block of the NG-PON2's QoS and contains the following traffic classes:

1. Fixed bandwidth (highest priority)
2. Assured bandwidth
3. Non-assured bandwidth
4. Best-effort bandwidth (lowest priority)

Guaranteed bandwidth consists of fixed and assured bandwidth. The fixed bandwidth will be assigned first regardless of the ONUs' offered load and overall traffic; as a result, any excess bandwidth is wasted. Next, the assured bandwidth will be assigned up to the provisioned limit or the subject ONU's satisfaction. After allocating the guaranteed part of the bandwidth, the non-assured should be assigned until the exhaustion of the surplus bandwidth pool or saturation of the ONU. The best-effort bandwidth then will be allocated to the ONU if it is not saturated.

It is noteworthy that ITU-T G.989.3 [27] inherits these specifications from the legacy ITU standards ITU-T Rec. G.984.3 [20] and ITU-T Rec. G.987.3 [21] and most of the details about DBA remains unchanged. Rather than mandating any specific DBA algorithm, ITU standards only specify the exchange of control messages between ONUs and the OLT. In particular, the DBA algorithm is not specified in detail [28].

GigaPON Access Network (GIANT) Medium Access Control (MAC) method [24, 29, 30] an ITU G.984.3 [20] standard complaint DBA algorithm is the baseline for most of the research papers on GPON DBA. GIANT implements the QoS specifications of the standard using four different T-CONTs (traffic container) types. Each T-CONTs is served every service interval (SI) with certain allocation bytes (AB) based on their queue occupancy reports.

Traffic Prediction Based DBAs

Traffic-monitoring DBA (TM-DBA) or non-status-reporting (NSR-DBA) is a method of dynamic bandwidth assignment that infers the dynamic activity status of the traffic-bearing entities within ONUs based on observation of idle XG-PON encapsulation method (XGEM) frame transmissions during upstream bursts [22].

In [31], a prediction technique is used to predict the arriving traffic in the ONUs' queues while the ONU is waiting for the next allocation. The predicted traffic is then added to the queue occupancy report to be sent to the OLT. The prediction scheme uses an average of several previous arrival records in each T-CONTs buffer in the past cycles while considering a weight for each record. P-DBA has reported improvement both in packet delay and loss rate compared to similar DBAs.

Further research has been carried out to improve the precision of the traffic prediction using fuzzy logic [32], data mining [33], least-square fitting linear prediction [34], and learning automaton [35]; all of which following the same goals, i.e., further reducing the scheduling latency and improving the prediction precision thus increasing the network throughput.

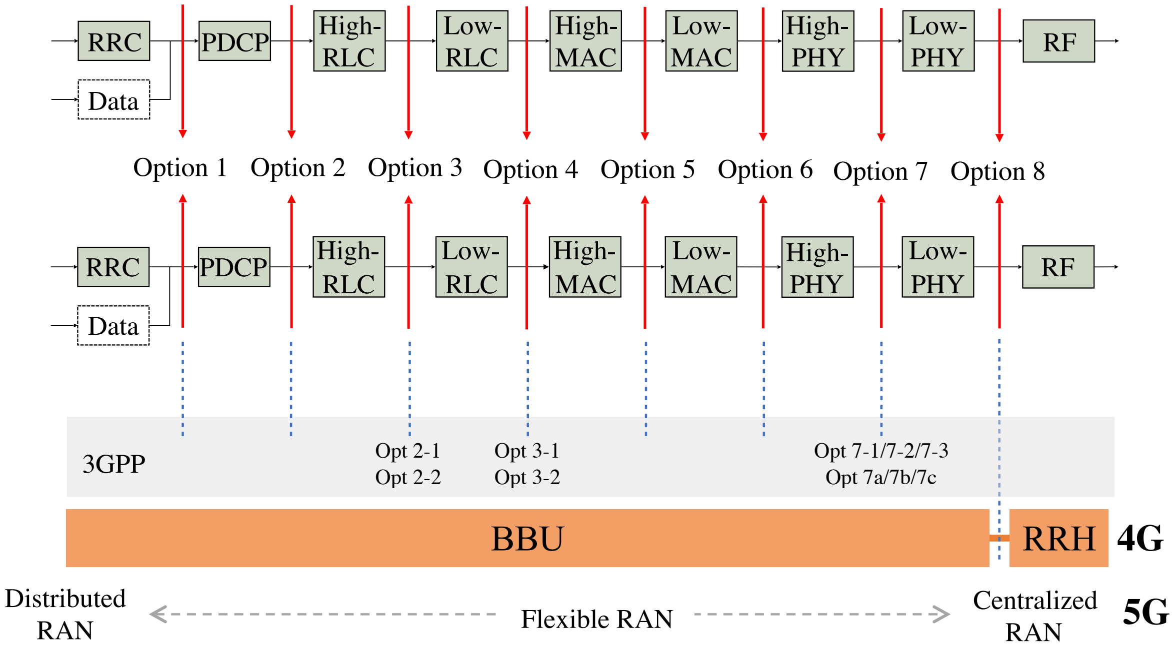


Figure 2.1: Different Functional Split Options [1]

Low Latency DBAs for Cloud Radio Access Network (C-RAN)

C-RAN is an architecture for cellular 5G networks which enables higher statistical multiplexing gains by decoupling the two main components of a cellular base station, i.e., Base Band Unit (BBU) and Remote Radio Head (RRH). The BBU is then centralized in a cloud environment. The pooling of the base band resources allows them to be shared between multiple RRHs and increase efficiency. However, this decoupling implies that the mobile traffic has to travel a considerably longer distance between the BBU and the RRH. In addition, since the RRH cannot process the traffic and has to simply transmit the raw In-phase/Quadrature (IQ) samples, it requires more transmission capacity. The portion of the network connecting the RRH to the BBU is referred to as fronthaul. Besides, other functional split options have been being studied [36] and proposed by different standardization bodies. Different functional split options are depicted in Figure 2.1. The required transport bandwidth and latency varies in different split options (see Table 2.1).

Fiber infrastructure is inevitably the only long-term solution for mobile back/fronthaul [37]. PONs are being widely investigated as alternative backhaul/fronthaul mobile transport solutions. The primary challenge, however, is the upstream scheduling mechanism, i.e., DBA that introduces further jitter and latency to the transmission as depicted in Figure 2.2. While the additional latency can be tolerated in traditional mobile backhaul and split options 1-3, it

Table 2.1: Transport bit rates and latency ranges at different functional split interfaces [1]

Protocol split option	Required downlink bandwidth	Required uplink bandwidth	One way latency (order of magnitude)
Option 1	4 Gb/s	3 Gb/s	1-10 ms
Option 2	4016 Mb/s	3024 Mb/s	
Option 3	[lower than Option 2 for UL/DL]		
Option 4	4000 Mb/s	3000 Mb/s	100 to few 100 μsec
Option 5	4000 Mb/s	3000 Mb/s	
Option 6	4133 Mb/s	5640 Mb/s	
Option 7a	10.1-22.2 Gb/s	16.6-21.6 Gb/s	
Option 7b	37.8-86.1 Gb/s	53.8-86.1 Gb/s	
Option 7c	10.1-22.2 Gb/s	53.8-86.1 Gb/s	
Option 8	157.3 Gb/s	157.3 Gb/s	

becomes an issue for mobile fronthaul and split options 4-8 as the latency tolerance reduces to a few 100 μsec. The authors in [8] have addressed this issue by proposing the communication of scheduling information between the upstream Long Term Evolution (LTE) scheduler and the DBA. This way, the DBA can grant upstream capacity in advance, bypassing the buffer status report mechanism and thus reducing the latency associated with upstream bandwidth grants. Similar schemes were experimentally evaluated in [38], using a 10G EPON prototype. In [39, 40], the authors propose to align the DBA engine with the LTE base station to assign the unused capacity to other services, such as residential broadband, taking advantage of the fact that in LTE's Time Division Duplex (TDD) system, upstream capacity is only needed in some of the subframes. To demonstrate the feasibility of the solution experimentally, the authors used a Field-Programmable Gate Array (FPGA)-based 10G EPON prototype and a Local Area Network (LAN) analyzer serving as a traffic generator. By both numerical simulation and experiments, the authors prove that the proposed method increases the throughput of the system significantly, and the mobile fronthaul transmission experiences less than 50 μs latency.

In [41], the authors propose a scheme to analyze the statistics of upstream transmitted traffic from LTE. Using these statistics, the DBA decides how to assign capacity to the RRHs based on the traffic from previous days. They have conducted experiments with results showing that the redundant bandwidth allocations can be reduced, and a fronthauling latency of less than 50 μs can be achieved.

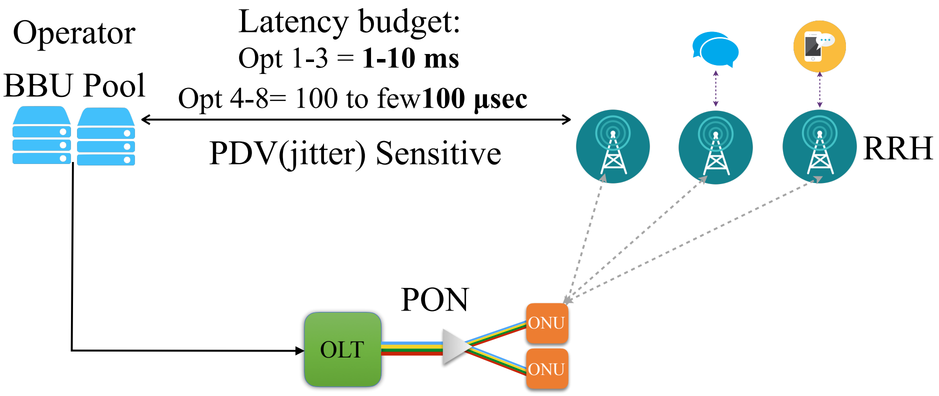


Figure 2.2: Fronthaul over PON

2.2 Network Sharing

A communications network is a shared resource that interconnects multiple nodes. Network sharing is a fundamental principle of link capacity statistical multiplexing, i.e., the overall link capacity is only a fraction of the total interconnection capacity required if all nodes attempted communicating at once. From the mid-1990s, the concept of sharing was also extended to cover the multi-tenant use of the network, where third party network operators compete with the incumbent national operator so that the same common infrastructure is shared across multiple competing entities. The degree to which infrastructure could be shared is limited, on the one hand, by physical and logical boundaries that separate resources, and on the other hand, by economic complexities such as settlements, agreements, and regulations that complicate the sharing process. Recently, revolutionary technologies such as SDN and Network Function Virtualization (NFV) have enabled network multi-tenancy that increases the flexibility and level of network control automation and management processes, in ways that were not possible before. Virtualization technology enables different entities to get access to a subset of the network resources while giving the illusion of fully owning that part of the infrastructure. This separates the operations of one tenant fully from other tenants while sharing the same physical infrastructure.

In the past few years, many 5G trials have been carried out worldwide. For example, up until early 2019, only in Europe, there have been 138 trials in 23 countries [42], often with partnerships between Industry and University [43]. Some of the trials were carried out specifically on Fixed Access Network Sharing (FANS), by vendors and operators, as reported in [44, 45], emphasizing the important role that infrastructure sharing plays in Fifth

Generation (5G) networks. The newest generation of cellular networks, 5G, is designed to provide higher capacity and to improve performance metrics such as latency, packet loss, and availability. The corresponding increase in infrastructure cost requires the network to be shared efficiently across many services and tenant operators. Densification of access points and the virtualization of the access network has thus become a fundamental principle in the design of 5G networks. In addition, the growth in infrastructure investment for the 5G networks is challenging the conventional standalone network ownership model. Operators can save between 20 and 55% in Capital Expenditure (CapEx) by sharing their assets, depending upon to what extent the infrastructure is shared [46]. The 5G Infrastructure Public-Private Partnership (5G PPP) [47] argues that new resource sharing business models are the key enablers for the success of 5G.

The principles of fixed access network sharing and its enabling technologies have been extensively explored in [48]. For instance, multi-wavelength systems, such as NG-PON2, can provide both high capacity, isolation, and flexibility of operation in shared networks. However, one of its main disadvantages is that it requires ONUs to be equipped with tunable lasers and filters, making their widespread deployment expensive. The Body of European Regulators for Electronic Communications (BEREC) has published a report [49] on the new forms of sharing PONs based on Wavelength Division Multiplexing (WDM) technology, including a questionnaire completed by 50 European network operators. More than 20 percent of the operators have mentioned that the expense of the NG-PON2 equipment was one of the main reasons why it is not likely that they will deploy NG-PON2. On the other hand, only four operators have considered wholesale wavelength unbundled services and the reuse of the passive network infrastructure as primary reasons for the network operators to deploy NG-PON2 [49]. Therefore, NG-PON2 does not appear to be the operators' choice to enable infrastructure sharing.

Considering cooperation and competition among operators, in [50] the authors study how the Swedish telecommunications business landscape changed throughout the different mobile network generations (GSM, 3G, and 4G) and competing mobile operators started to share network resources. However, this trend changed with the deployment of 4G networks, where reduced equipment costs and re-usability of the base station sites between 3G and 4G played a role in disincentivizing operators to share. Based on the market reports in [51], the upgrade pattern to 5G will be radically different from 3G and 4G, where an increment of 23% in

CapEx is expected between 2018 and 2025. In [52], the authors conduct a cost assessment studying how PON/Fiber-to-the-Home (FTTH) network could affect factors such as initial investment, cost per home connected, and the payback period. Their study covers the most popular optical access technologies and standards, namely GPON, XG-PON, TWDM-PON, and WDM-PON in urban and suburban regions. They conclude that while employing a network sharing scheme increases the cost per home connected and the payback period, the required initial investment is significantly reduced.

However, realizing considerable cost savings will require the operators to think beyond sharing only feeder fiber cables or site-reduction [53]. In addition to cost reduction, infrastructure sharing can facilitate the expansion of coverage, therefore, helping the operators grow their customer base and access new sources of revenue. On the other hand, the advantages of network sharing come at the cost of incentivizing operators to share their infrastructure and resources. In some countries, the regulator may attempt to enforce sharing [3], but this was met with limited success as operators tried to circumvent regulations by using legal loopholes, for instance, by not providing the required interfaces. As the cost for 5G network deployment soars, the potential reduction in the Total Cost of Ownership (TCO) achievable through new models of infrastructure sharing will provide a better driving force than the legacy regulatory enforcement.

2.2.1 Aggressive Competition and Net Neutrality

The topic of Net Neutrality is out of the scope of this dissertation. However, we find the following argument to be an essential background to the formation of the research questions addressed in this dissertation.

The beginning of the research leading to the present dissertation coincided with AT&T, the world's largest telecommunications company, acquiring *Time Warner*, now WarnerMedia, a mass media corporation including cable channels *CNN* and *HBO* and the *Warner Bros.* On the other hand, Comcast, who already acquired NBC Universal in 2011, made a bid for Sky network and successfully outbid the competitors and completed the acquisition in 2018. These acquisitions are considered to be the response of these conglomerates to the market disruption caused by Over-the-Top (OTT) streaming services such as Netflix. The telecom giants consider new and creative service providers as a threat to their revenue. Nonetheless, the predatory practices are not limited to nervous acquisitions. For example, Comcast has previously slowed down the Netflix's streams for its broadband customers in 2014 to the extent which forced Netflix to negotiate a deal preventing Comcast from slowing its content down. Netflix reportedly had similar deals in place with AT&T and Verizon.

> *"once you pay it's like blackmail, they've got you, there's nowhere else to go. They'll just keep raising the price in a market where prices [for transit] are falling."*
> Cogent's CEO (backbone network provider of Netflix) [54].

It has commonly been assumed that these turn of events led to the Federal Communications Commission (FCC) 2015 ruling enforcing net neutrality in the United States [55].

The above opening argument is to set the context on the predatory conduct of bigger operators towards innovative service providers and is stated to emphasize the importance of designing network sharing market ecosystems with the ability to prevent such conduct. Similar aggressive competitive dynamics could be expected in a network sharing ecosystem where market controlling power is concentrated in the hands of a single or few dominant operators or Infrastructure Providers (InPs).

2.3 Network Virtualization

The general architectural guidelines for FANS were set out by the BroadBand Forum (BBF) in the TR-370 standard [56], which defines mechanisms to enable sharing of multi-service broadband access networks for new Virtual Network Operators (VNOs), using European Telecommunications Standards Institute (ETSI) NFV standards. The standard is currently being updated [57], to further specify the roles of VNOs and InPs, as well as improving the definition of the interfaces between the two.

Based on the guidelines in the recent standards, SDN and virtualization technologies can facilitate sharing primarily in two ways:

1. By providing simplified and standardized interfaces to connect to other operators' networks.
2. By virtualizing the critical network control functions and provide customizable functions for the guest operators.

In this section, we will briefly review the state-of-the-art efforts to adopt virtualization and SDN to address the challenges associated with network sharing.

2.3.1 Software Defined Networking

The growing demand for new services, along with the prevalence of multi-vendor/operator networks, is increasing the control complexity of the network. SDN tackles the inflexible nature of the legacy networks in which altering a minor feature in the network can impose high costs on the network operators. This is achieved by minimizing the control functions in the network's edge components and centralizing these functions in a unified control plane, which is physically closer to the network operators' central office. In other words, every edge device in the networks runs none or just a part of the control plane functions as opposed to the traditional distributed approach in which each device would run a full instance of a control plane. The ratio of control plane functions, which are to remain in edge devices or to be moved to a centralized controller, forms a trade-off, and it is a vast research domain by itself [58]. The separation of the control and data planes is indeed one of the fundamental and more controversial tenets of SDN [59]. To clarify, in this context, we refer to mechanisms that determine the flow table entries in any network component as a control plane and the element which acts based on these tables as a data plane. It is noteworthy that the control plane is capable of memorizing the past control instructions. We will not endeavor to prove the nobility of SDN and its potential advantages for telecommunication networks as this has been comprehensively addressed in the literature [60]. Instead, we will contend with assuming that it can have a positive effect on the network performance as a fact and will describe the cases in which SDN can be of great assistance to telecom networks. The rest of this subsection is dedicated to clarifying the concepts which have been correlated with SDN in the literature.

Control and Data Plane Split

In the pre-SDN era, scaling the control plane would have required the network operators to follow a hardware upgrade planning path in which they would not have been able to develop the network on-demand. Hence, the development of the network depended on the availability of assets to invest in hardware and, consequently, sites to accommodate them. In the process of upgrading the control plane functionalities, lots of capital were wasted while unnecessarily upgrading the data-plane together with control-plane since they were coupled. The equipment vendors' approach to help this situation was separating the control and data planes apart so that they could evolve and scale independently. The separation of the control and data planes is not a concept initiated in parallel with SDN. i.e., the control and data plane have been implemented separately in dedicated processors in the majority of home switch/routers manufactured in the last decade or so [59]. What is new is externalizing the control plane, whether absolutely (unlikely) or by leaving behind some of its functionalities to remain in the data plane.

Control Plane Centralization

Providing an inclusive and unified view of the network for applications and simplification of programmatic control is an advantage that can be achieved by the centralization of the control plane [59]. In other words, data planes from the converged network (wireless-optical in this case) components can communicate and interact with each other through the centralized control plane. An advantage which would be very hard, if not impossible, to offer in a distributed control plane architecture with control planes scattered around far edges of the network.

Network Programmability/Softwarization

Programmability of network components is not a new concept. However, what SDN has to offer is the interactive programmable network components, and even one step forward with network functions. The ultimate target here is to facilitate multi-directional communication between these softwarized components. In [61], the authors have surveyed the most recent research initiatives on programmable networks while exploring the research issues associated with programmable networks within data and control planes. The shift from the domination of hardware designed radio systems to the mostly software implemented design has been referred to as Software Defined Radios (SDRs) [62]. SDRs can implement most of the communication functions in software, except Analog-to-digital and digital-to-analog conversion [61]. Details of SDRs are extensively reviewed in [61, 63] and is out of the scope of this dissertation. In the context of heterogeneous networks, this capability can be fully exploited only if these software-defined radio functions can communicate with other software across the entire network. In [64] the authors propose a cross-layer architecture to benefit from both SDR and SDN characteristics. Their proposed cross-layer controller resides between the SDN and SDR layer controllers to oversee spectrum resource provisioning.

NFV [65] is another concept related to network programability. The idea of NFV is to allow the virtualization of network functions to run on commodity servers. Including Internet Protocol (IP) Virtual Network Functionss (VNFs) (e.g., load balancing, firewalls, security) [66] or transport control functions such as Path Computation [67].

2.3.2 Service Diversity in PONs

Homogeneous PON sharing (e.g., sharing the network between broadband companies) is not expected to incur serious technical challenges particularly in terms of resource scheduling since their service requirements such as QoS are somewhat aligned. On the contrary, accommodating mobile service providers in the same PON as broadband providers requires an ultra-flexible and customizable control plane. Such a heterogeneous scenario necessitates a new collaboration model to allow tenants to have adequate control over the resources leased from the infrastructure provider [68]. Thus new radical thinking is needed to enable heterogeneous PON sharing. In the rest of this section, we study the technical challenges of service diversity in PONs and see how virtualization technology can be utilized to overcome such challenges.

The efforts for standardization of PON and providing updated solutions from organizations such as ITU, IEEE, and BBF have motivated interest from mobile operators to consider PON as an access solution to reach their base stations. This will further diversify the network requirements and will make the shared PON's QoS management more complex. The employment of PONs as backhaul and fronthaul access in cellular networks and 5G networks have recently been the central focus for many researchers [69, 70].

One of the essential features of PON is the DBA algorithm, which provides burst level scheduling for upstream transmission of the PONs. DBA is responsible for collision prevention, utilization of the upstream bandwidth, and providing the required QoS to satisfy possible SLAs. Therefore DBA is one of the essential parts of the PON control plane that can satisfy the requirements of the users. However, in a heterogeneous scenario, while multiple parties are sharing the same PON, their requirements, e.g., latency and QoS, can be different and sometimes even conflicting.

The well-known trade-off in DBA is between QoS, and bandwidth allocation accuracy versus latency. In other terms, the DBA algorithms with higher accuracy in reporting queue statuses achieve a better QoS while more precise reporting of the queues also imposes a high latency on the PON.

While bandwidth efficiency can be essential for residential broadband access, an essential requirement for C-RAN is a very stringent latency threshold around 150 microseconds [36]. Conventional DBAs in TDM-PON are incapable of yielding latencies in the order of several hundred microseconds [71], and DBAs capable of providing ultra-low latency are desired. Some examples of such low latency DBAs have been proposed in [8, 72, 73] mainly based on cooperation with an LTE scheduler to map the wireless resource blocks on real-time to PON Bandwidth Maps (BMaps) and achieve low-latency.

On the other hand, TV providers are interested in providing 4K/8K resolution programs which require up to 120 to 300 Mbps guaranteed bandwidth when considering the simultaneous program recording capabilities [74]. Thus, a highly efficient bandwidth allocation would be of more importance for a TV provider rather than latency. Therefore a mobile network operator would be more interested in implementing its version of DBA to meet its requirements. Consequently, In case that mobile service providers and TV providers are going to share a PON, they will desire to employ their customized version of DBA to meet their requirements. This customization is not possible in the current OLTs' control plane, and all the tenants are compelled to settle for the DBA implemented by the InP or the vendor.

The most obvious solution for a multi-tenant PON with the highest customization of the technology is using multiple OLTs (and consequently service-specific DBAs for each OLT) over the same Optical Distribution Network (ODN). In [75] the authors propose upstream and downstream DBA algorithms for such multi-OLT PONs. They introduce distinct DBAs to manage the upstream/downstream scheduling. However, dedicating an OLT for each PON tenant will impose more cost to the InPs resulting in the increment of CapEx and Operating Expenditure (OpEx), reducing the bits per joule energy-efficiency factor. It is worth mentioning that the popularity of PONs in access networks relies on its passive nature, therefore increasing the ratio of active elements to the passive elements will result in a potential decline in PON's popularity. Therefore a single OLT topology while exploiting the features of the

OLT to host more than one tenant is more desirable.

2.3.3 PON Virtualization

The Central Office Rearchitected as a Data Centre (CORD) [76] project has been proposed to design a new telco central office architecture aiming to replace proprietary purpose-built hardware components with software running on commodity servers and off the shelf white-box switches and access devices. Therefore, representing the central office as a data center rather than a traditional architecture that often includes up to 300 unique hardware devices with a broad range of technology and requiring huge CapEx and OpEx to operate. CORD uses XOS [77], a service orchestration layer built on top of OpenStack [78] and ONOS [79] that manages scalable services running over CORD. The Open Network Operating System (ONOS) is a SDN controller platform that enables virtualized network functions to communicate the control messages with the whitebox hardware through the southbound interface. The southband API in ONOS supports the most prominent communication protocols such as OpenFlow and NETCONF and also Border Gateway Protocol (BGP) and Simple Network Management Protocol (SNMP) to allow backward compatibility and support for older systems. OpenStack controls the computing, storage and networking resources that are to be assigned to each virtual function. The CORD project is led by Open Networking Foundation (ONF) and is supported by a considerable number of collaborators and partners, including some major service providers and network equipment vendors.

The CORD architecture creates a suitable environment for realizing the centralization approaches such as C-RAN. The project consists of three sub-projects, namely Residential CORD (R-CORD), Mobile CORD (M-CORD), and Enterprise CORD (E-CORD). Each sub-project is a proof of concept use case for the CORD framework for demonstrating its ability to accommodate a wide range of technologies in a software-defined architecture.

M-CORD is aiming to enable 5G on CORD by introducing concepts such as disaggregated/virtualized Radio Access Network (RAN). The key components of this project are virtualized BBU (vBBU) and the Remote Radio Unit (RRU).

R-CORD, on the other hand, is focusing on the last mile access networks for the residential market. R-CORD is using the PON as its infrastructure and implements the SDN idea by virtualizing more network components both from the telco side and client sides such as OLT and Customer Premises Equipment (CPE), respectively. Virtualizing network components lets them move one by one the functionalities from hardware close to the customer's premises to the virtual machines hosted in the central office's data center while replacing those components with simple white-box hardware and dramatically reduce the OpEx and CapEx.

DBA Virtualization

The current inflexibility of the PON makes it practically impossible for the operators to implement new technologies, and as a result, they have to develop an individual system for every service. Furthermore, this remains a bottleneck for the realization of multi-tenancy as different services cannot coexist on the same network. Nippon Telegraph and Telephone (NTT) Labs has recently introduced the Flexible Access System Architecture (FASA) [80]. They aim to build a modular network in a way that each module is individually customizable. At the same time, these modules can be combined to build a network that can meet diverse requirements and, as a result, can host different services. In particular, we are interested in one of their use cases that enables the accommodation of mobile service operators by DBA Replacement. In this use case, the DBA is implemented as a FASA application, meaning that the network operators can conveniently implement their DBA algorithm of choice. However, it is unclear how different DBA applications can coexist in their model.

In [81], the authors have proposed to define a software instance of the DBA per each domain of a multi-domain network. The Domain DBA (DDBA) function divides the bandwidth allocation to three steps. First, to assure isolation between the domains a maximum bandwidth is set for each DDBA. Second, each domain chooses a bandwidth allocation policy (e.g., fixed, best effort) and calculated the allocation based on that policy. Finally, a certain amount is allocated to each ONU of every domain. Nonetheless, it is ambiguous in their proposal whether if the allocation policy is only limited to choosing a QoS class or it also means that different DBA algorithms could be allocated to the domains.

2.4 Auction Theory for Communications

As 5G networks promise unprecedented support for novel heterogeneous services, new business and ownership models are required that take into consideration their entire value chain, including the InPs, network operators, and OTT service providers. To achieve the target sharing level, all parties will have to collaborate and cooperate regardless of the potential competition among them. This is not an easy goal to achieve as the operators often have conflicting interests, which could pose serious obstacles to their commitment. Thus, robust mechanisms to assure the commitment of all the parties are required. The study of interactions among parties with conflicting interests is not a new field, neither in economics nor in telecommunication networks. The application of game theory to economics is dedicated to resolving such situations, where the strategic interaction between decision-makers are involved in a collective decision-making process. These parties might have conflicting and contradicting interests; therefore, they are more committed to achieving a better outcome for themselves than for the system as a whole.

Game theory has been widely used to solve collaborative resource sharing problems in a wide range of subjects, including computer science, telecommunications, management, etc. One of the most successful examples of game theory applied to resource sharing is the wireless spectrum sharing in telecommunication networks. Initially, auction theory was used in primary spectrum licensing, which involves one-time nationwide auctioning of the scarce spectrum, usually conducted by the governments. However, such long-term fixed spectrum licenses (e.g., latest ComReg's 3.6 GHz Band Spectrum award for the duration of 15 years [82]) to primary users leads to low utilization of the spectrum (more than 70% of the radio spectrum, in certain times or geographic locations [83]). The inefficient use of spectrum has prompted the regulators to investigate the secondary use of the licensed spectrum, where the primary users can improve the utilization of the spectrum allocated to them by enabling the reuse of the underutilized bands by secondary users [84]. The fixed access sharing is very similar to the spectrum licensing, as for instance, current sharing methods of dedicating entire fiber or wavelength channels lead to low utilization of the access network capacity. Thus, an opportunistic secondary sharing scheme could be adopted to assure higher utilization of the network.

Auctions are well-established tools to solve resource allocation problems in telecommunication and computer science research. What is common among these research works is that they are dedicated to efficient resource allocation while maintaining the incentives for all the players. In [85], the authors provide an introduction to the auction literature for computer scientists. The applications of the auction in computer science and telecommunication systems range from resource management in cloud networking [86] to digital advertising [87] and wireless spectrum allocation [88]. In [88], the authors have carried out a comprehensive survey of auctions and their application in resource allocation problems in wireless networks. However, the application of auctions is not limited to spectrum sharing. The authors in [89] have proposed an iterative double auction mechanism for Offloading the traffic of the mobile operators to third-party owned Wi-Fi or femtocell access points. Furthermore, auction-based solutions have also been proposed to manage the spectrum resources of device-to-device communication in cellular networks [90].

Different auction formats are designed to incentivize truthful bidding. The Vickery-Clarke-Groves (VCG) [91] is one of such mechanisms which is designed in a way that provides incentives for the buyers to bid truthfully. The VCG mechanism satisfies all the three essential auction properties, i.e., dominant-strategy truthful bidding, weak budget balance, and individual rationality. The truthfulness property simplifies the optimal bidding strategy of the buyers and consequently leads to the lowering of expenditure on resources learning about competitor buyers' strategies [92]. VCG tries to exclude the traders' announced value from the trade price determination process. This technique eliminates the chance of untruthful reporting from traders with the hope of increasing their utility by paying less (as a buyer) or receiving more (as a seller). VCG auctions have been widely employed in telecommunication networks ranging from spectrum sharing [93] to resource allocation in cloud computing [94]. Many different auction mechanisms have been used in the literature, and we will not endeavor to survey and present a classification of them and will rely on the classification presented in [88].

2.4.1 Double Auctions

Double auctions have received less attention compared to one-sided auctions. Achieving economic properties is more complicated for double auctions in comparison so one-sided auctions. The *impossibility theorem* states that no bilateral trading mechanism (e.g., double auction) can simultaneously achieve all of the economic properties together with optimal allocative efficiency [95]. Therefore, an inevitable trade-off is imposed on the system that needs to be addressed by prioritizing the economic properties by how much they would affect the outcome of the system. Thus choosing one of the properties to compromise to achieve the rest.

The most influential work on double auctions was published by McAfee [96]. McAfee acknowledged the impossibility theorem stated by Myerson-Satterthwaite [97] and proposed a dominant strategy double auction that achieves asymptotic efficiency ($\frac{1}{n}$ efficiency loss where n = the number of traders, i.e., it trades the Walrasian quantity minus one unit) while maintaining the desirable economic properties in a single-item single-unit market setting. The authors in [98] have tried to solve the two-sided multi-unit market problem by running two separate one-sided VCG auctions with a reserve price, one for the sellers and one for the buyers.

In SBBA [99], the authors set a single trade price for all traders, in all cases. This may lead to excess supply, and to handle the excess supply, a lottery is done between the sellers. At most one seller, selected at random is excluded from trade. Hence, the expected total-gain-from-trade of SBBA is the same as McAfee's. An advantage of SBBA is that it is strongly budget-balanced. However, this is not an advantage in our market setting since the auctioneer desires a broker fee for conducting the auction.

In [100], a multi-unit double auction (MUDA) mechanism is proposed, which split the market into two sub-markets, by sending each trader to one side with equal probability. Then, on each side, it calculates the Walrasian market price and lets each side's traders trade on the other group's prices. This way, it achieves incentive compatibility and asymptotic efficiency. However, this mechanism also is not fit for our market as; first, it is strongly budget balanced as the previous mechanisms, i.e., does not leave any surplus from trades for the auctioneer and also it requires a large number of traders to form two distinct groups or sub-market, and realistically the multi-tenant PON market is not large enough.

In [101], the authors have proposed a market model for secondary market spectrum sharing, which has many similarities to our multi-tenant PON market. The authors in [101] successfully applied a McAfee [96] style double auction to their multi-unit auction market. Their mechanism achieves Individual Rationality (IR), Incentive Compatibility (IC), and weak budget balance, which is desirable for our market as well. *Xu et al.* [101] also achieved asymptotic efficiency in their mechanism. However, it is not realistic to assume any PON system with such a large number of VNOs to be enough to qualify to be considered an asymptotic setting. Thus, our best hope is to try to improve the non-asymptotic efficiency. The work of *Xu et al.* will be the baseline for the work in this dissertation, which is further discussed in chapter 4.

2.5 Blockchain and Smart Contracts Technology

Widespread deployment of the 5G networks will require the network operators to assure new revenue streams in order to compensate for the capital expenditure incurred by provisioning of the new infrastructure. New services will require novel business models as they are unlikely to fit within current network ownership models, where an OTT or a vertical industry has to undergo manual negotiations to acquire network resources to deliver services to its customers. Therefore, automated business processes become vital as they can facilitate the utilization of the network infrastructure for new services as they appear.

Blockchain technology has already been adopted by a wide range of industries to automate complex business processes and workflows [102, 103]. Blockchain technology helps these enterprises to move away from the Business Process Management (BPM) models where a third party organization stores the business information in a central repository and controls the transactions in cross-industry environments. This way, they both avoid the single point of failure and allow enterprises to gain control of their data.

The main innovation of blockchain technology in the context of cryptocurrencies is preventing double-spending while offering a distributed alternative to the costly real-world central bank system, which provides the required mechanisms to avoid double-spending. In short, blockchain technology provides a robust solution for trustable book-keeping. Blockchain technology is being considered as the primary trust solution when a trustworthy central book-keeper is absent. Example applications are government and private management, electronic voting, authorship and ownership, etc. [104], while more are currently under study, such as applications in pharmaceutical supply-chain [105], consumer electronics [106], smart-cities [107], privacy protection in health-care [108] and insurance [109].

It was later realized that the cryptocurrency applications do not fully utilize the potential of blockchain technology. In other words, the same decentralized consensus mechanism could be used to maintain the same level of trust for the logic-enabled transaction rather than simple book-keeping. Therefore, the idea of blockchain was further complemented by the concept of smart contracts, which introduced blockchain technology, not only as a robust book-keeping tool but also as an effective automation platform that can address many trust-related concerns in multi-party business ecosystems. A Smart Contract is an immutable piece of logic (computer program) that enhances the distributed ledger technology with self-enforcing pre-negotiated agreements. Therefore, a smart contract can automate the enforcement of business processes without relying on a central authority.

In this dissertation, we are particularly interested in automating the process of dedicating a set of network resources to a VNO on-demand for a given period of time. Furthermore, giving the ability to the VNOs to trade their excess resources with others. More specifically, we are interested in studying the implementation of bilateral resource trading markets using blockchain as the data storage structure solution and smart contracts as the tool for the execution of the market mechanisms and inter-carrier financial settlement. The examples of such bilateral trade markets in telecommunications industry include: resource allocation in NFV markets [110], promoting femtocell access [111], mobile crowd sensing with budget constraint [112], spectrum allocation [113] and multi-tenant PONs [114]. The common challenge among these resource markets is the fact that they rely on a third-party entity to both store the private financial information of the participants and execute the auction mechanisms which directly determine the allocation of the resources. Whoever, in real business ecosystems, often no central entity has the full trust of all the partners due to competition. As further discussed in chapter 5, smart contracts can replace the reliance of our market mechanism (see chapter 4) on a central entity (in this case an InP).

Blockchain technology is most popular as the distributed-ledger technology behind Bitcoin and other crypto-currencies. However, blockchain has been progressively re-invented as more and more industries have shown interest in its potential for enabling novel business models. The initial blockchains, including Bitcoin's, came as public blockchains, meaning that the reading access to the ledger is not limited to any particular group as the privacy of the users is protected by the pseudo-anonymous nature of the network. While public blockchains are suitable for applications such as crypto-currencies, in enterprise ecosystems, this could become an issue due to the confidential essence of the information. Therefore, private blockchains were introduced to preserve the privacy of the participants. Quite similarly, the difference between permissionless and permissioned blockchains relies on the distinct way they control the contribution of the participants (writing access) to the ledger. In private and permissioned blockchains, a form of Membership Service Providers (MSP) is used to control and authorize access to the blockchain. Hyperledger Fabric [115] is the most prominent permissioned open-source blockchain platform designed for enterprise ecosystems, and it is maintained by the

Linux Foundation. The major components of a blockchain application/network are introduced in the rest of this sub-section with a focus on the Hyperledger Fabric framework, which we use for the experiments throughout this dissertation.

2.5.1 Enterprise Blockchain: Hyperledger Fabric

A number of purpose-specific frameworks and tools are being developed under the Hyperledger's umbrella for the use-cases ranging from finance and banking to the Internet of things, supply chain management, and manufacturing. Hyperledger Fabric is one of the frameworks which provides a permissioned distributed ledger technology for cross-industry applications, i.e., where only specific entities are allowed to participate. The main features of the Hyperledger Fabric platform are as follows:

1. It has a modular architecture that allows plug-and-play implementations of different functions/components such as consensus, membership service, etc.
2. It uses open-source container technologies (i.e., Docker) to host different components of the blockchain network.
3. It makes use of permissioned membership management and access to the ledger.
4. It allows for chaincode (smart contracts) to be written in various programming languages (e.g., Go, JavaScript, or Java) while other blockchain platforms only allow specific languages (e.g., Solidity in Ethereum).

A blockchain application is composed of multiple nodes with various roles, communicating with each other to reach an agreement on a final state of the ledger. The major concepts associated with a Hyperledger Fabric network are introduced in the following paragraphs.

The Shared Ledger The biggest innovation of blockchain technology is the distributed record-keeping capability that it provides. In the core of every blockchain, there is an append-only shared ledger. This ledger is distributed on multiple nodes over the network and is kept in synchronization using the consensus protocol. The novelty of blockchain's record-keeping process is in the method data is stored as a series of blocks chained to each other using cryptographic hashes. A Fabric network might contain multiple ledgers.

Organizations The blockchain network consists of one or multiple organizations who are contributing resources to the network while being able to process their transactions with

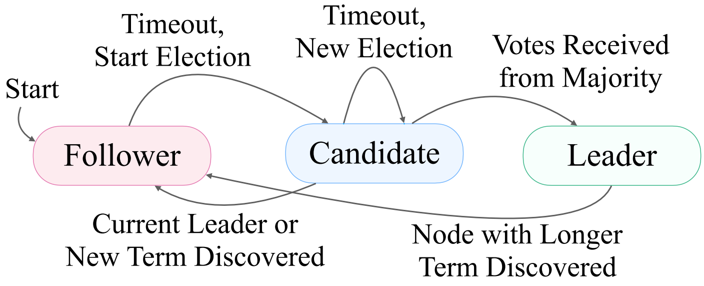


Figure 2.3: Leader Election in Raft Consensus

other participants. Organizations host peers and other components of the network and each maintain a copy of the ledger(s).

Consensus Protocol The heart of the ledger appending process is the consensus protocol, where the blockchain nodes come to an agreement on whether or not to add a block proposed by one of the parties to the ledger. Early blockchains used Proof of Work (PoW) based consensus that is proven to be extremely resource consuming. Therefore numerous new consensus protocols have been proposed. While their description falls outside the scope of this dissertation, we outline the Raft protocol [116] used in the experiments of this dissertation. Raft solves the problem of achieving an agreement between multiple participants on a shared state even in the face of failures if the majority of the nodes are still up. In Raft [116], the participating nodes choose a leader with a certain term during which the other nodes are the followers of the leader. During its term, the leader continuously sends a heartbeat to its followers to maintain authority. An election is triggered when one of the followers faces time out waiting for a heartbeat from the leader. Figure 2.3 depicts the different states of the nodes during the elections in the Raft protocol.

Network Peers The network peers (nodes) have different responsibilities depending on their role and the blockchain framework. In PoW based blockchains, these nodes are typically divided into miner nodes and validation nodes, with the former taking part in solving the PoW hash problem on top of its validation role. In Hyperledger Fabric, the main types of peers are endorser peers (which receive the transaction proposal, run the smart contract and endorse the transaction) and the orderers that are tasked with ordering the transaction and reaching the consensus on the final block.

Smart Contracts (chaincodes) The logic of the blockchain operation is implemented as a smart contract (or chaincode in Hyperledger Fabric). This is a piece of code that either defines the terms of the transaction or an enforceable function depending on the outcome of a transaction (e.g., a penalty for not meeting a certain clause in the contract).

Channels Channels in Hyperledger Fabric allow the participant organizations in the network to have a virtual blockchain network within the broader blockchain network without needing to replicate the nodes (e.g., hardware resources, etc.). This enables further privacy measures for more complex transactions and logic in the blockchain. In addition, Hyperledger Fabric allows multiple ledgers per channel.

2.6 Sharing Motivations and Implications

Having reviewed the existing literature relevant to the scope of this dissertation and briefly discussed the available technologies, we are now in a position to provide a response to the question "*What are the motivations and implications for optical access network sharing?*"

The identified motivations for optical access network sharing are:

- Reducing CapEx and OpEx by active and fine-grained sharing of the network resources, therefore, benefiting from the multiplexing gain.
- Ease of market entrance enabled by lower cost of delivering services to the end-users.
- Cultivating innovation made possible by facilitated market entrance for small innovative service providers.
- Competitive market with diverse players as opposed to the conventional oligopolistic network infrastructure wholesaling.

We also recognize the following implications of optical access network sharing:

- Multi-Service coexistence over the shared network infrastructure implies the necessity for providing the operators with more control over the network functions.
- Sharing incentives are to be provided for competing operators.
- New network ownership models entail the demand for decentralized control of the infrastructure sharing market.

3 DBA Virtualization to Enable PON Multi-Tenancy

DBA Virtualization to Enable PON Multi-Tenancy

> *"Do not fear to be eccentric in opinion, for every opinion now accepted was once eccentric."*
>
> —Bertrand Russell

The current scene on the broadband/mobile operators' market is an oligopoly, where novelty is limited by the market development policies of a hand-full of operators. The cost of entering this market is unaffordably high for smaller service providers who could bring considerable revenue to the access market by introducing new services. Sharing the last mile of access networks, which is the most Capital Expenditure (CapEx) demanding part, can dramatically reduce the required initial investment and facilitate market entrance for new operators. However, the current sharing methods, especially in fixed access networks, operate at too a high-level (e.g., Virtual Unbundled Local Access (VULA)) where they are not capable of providing enough control over the service provided to the customers [7]. Other proposals exist for low-level access, which typically translates in assigning a dedicated wavelength to a second operator. However, besides being inefficient, they are currently hindered by the fact that multi-wavelength Passive Optical Network (PON) (e.g., Next-Generation Passive Optical Network 2 (NG-PON2)) has not been widely deployed due to its high cost (see section 2.1). Therefore, we propose a new sharing technique for PONs, which meets the above-mentioned methods in the halfway by providing frame-level scheduling control for the operators while being more affordable and easier to attract new entrants [117]. PONs are cost-effective solutions for providing highly capillary connectivity to heterogeneous services, serving residential users, mobile cloud-RAN, and next generations services. Examples are haptic feedback for medical applications or reliable and timely exchange of control messages and camera streams in automotive applications. Some of these new services will, however, require stricter Quality of Service (QoS) than simple committed rate assurance, including latency and jitter targets.

From a PON perspective, this requires the development of new Dynamic Bandwidth Allocation (DBA) mechanisms, which have become the focus of recent research. Virtualization of the DBA process can provide strict-QoS (i.e., capacity, latency, and jitter assured services) over a multi-tenant environment. PON networks are considered a strong candidate for providing networks' services to 5G networks and beyond [118]. The lack of control over scheduling remains the single most significant technological barrier in PON sharing. In conventional PONs, the DBA is typically implemented as a hard-coded function on the Optical Line Terminal (OLT) and cannot be customized to meet the diverse demand of the tenant Virtual Network Operators (VNOs) providing heterogeneous services. As mentioned in section 2.3, numerous initiatives (including CORD [76], and BroadBand Forum (BBF)'s TR-370 [5]) are proposing solutions based on network virtualization technology. In the next section, we will elaborate on the importance of providing scheduling control for the operators and describe the proposed virtual DBA (vDBA) concept and architecture.

3.1 DBA Virtualization

PON is a point-to-multipoint optical access technology, which requires scheduling in the upstream transmission to avoid collisions between the data sent by the ONUs. DBA is a process that assigns time slots to each Optical Network Unit (ONU) for upstream transmission. The outcome of the DBA process is the transmission schedule for the ONUs, i.e., "Bandwidth Map (BMap)". Figure 3.1 depicts the format of the XGS-PON [119] BMap partition and an allocation structure. The BMap is generated by the OLT and broadcast to all of the ONUs in every 125 microseconds (i.e., the duration of a PON frame). The finest granularity allowed for each allocation structure is 16 bytes. Thus, each BMap may contain up to 9720 allocation structures for a 10 Gb/s upstream channel. ITU standards identify two DBA classifications. The first type is status reporting (SR) DBA, which schedules the transmission based on the definite reports of buffer occupancy of the ONUs and generates a precise allocation based on it. The second type is non-status-reporting (NSR) DBA, which bases the scheduling on the information acquired from traffic monitoring. The SR DBA provides higher precision but imposes some latency due to the exchange of control signals [120].

Current PONs fail to support the diverse range of requirements associated with the next generation of services (for 5G and beyond). For instance, current PONs cannot be used to

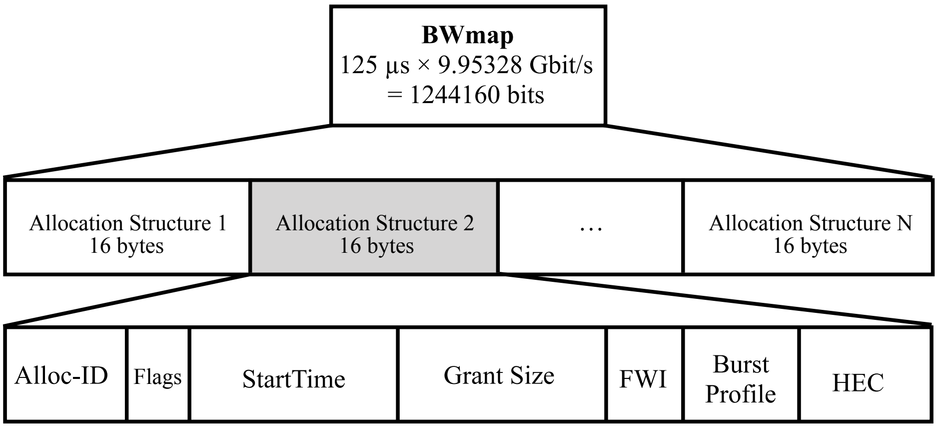
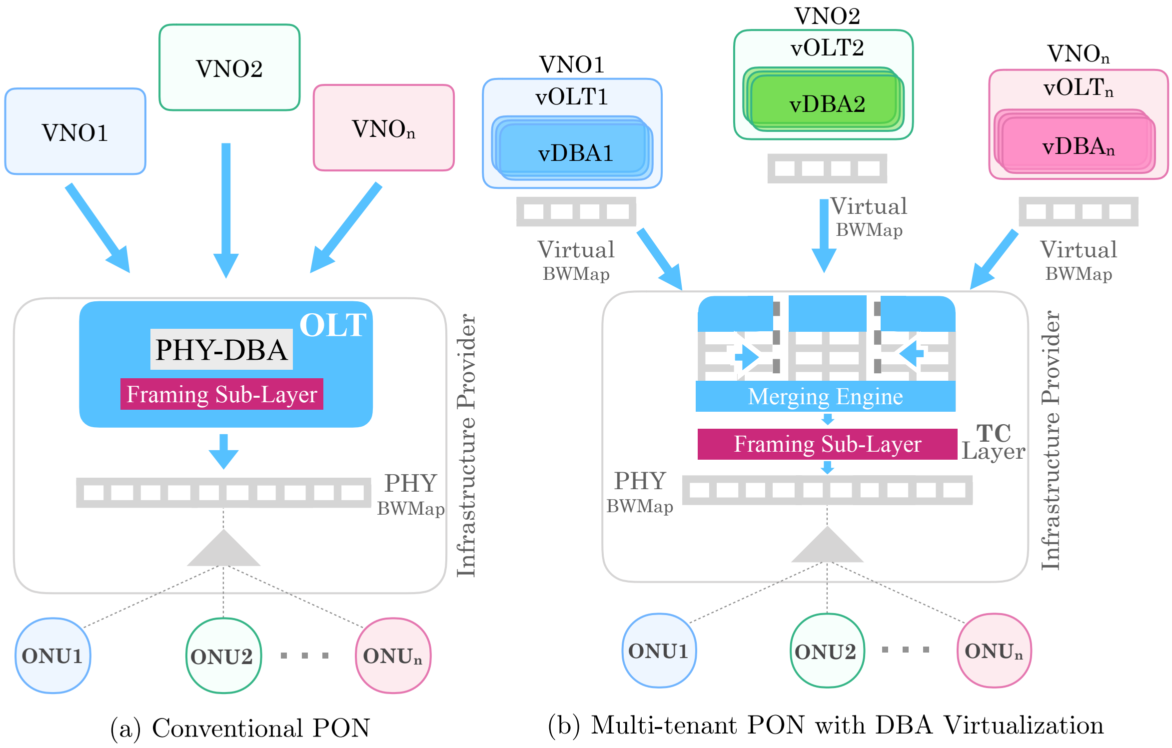


Figure 3.1: XGS-PON BMap allocation structure format

provide connectivity between Remote Radio Head (RRH) and Base Band Unit (BBU) in mobile Cloud-RAN applications, as it cannot meet the required delay budget, which is of the order of few hundreds of microseconds [121] unless if a static fixed bandwidth is allocated. Thus, the research community is investigating new DBA algorithm designs e.g. predictive [122] or unified vDBAs-Wireless scheduler [121], to provide support for these ultra low-latency services.

3.2 virtual DBA (vDBA)

Figure 3.2 shows the comparison between today's PON and the proposed multi-tenant PON, which implements the vDBA concept. In traditional PONs, a single DBA scheme is implemented in the OLT hardware (Figure 3.2a). From hereafter, we shall refer to the DBA scheme implemented in hardware as physical DBA (PHY-DBA). In this architecture, only the Infrastructure Provider (InP) controls the PHY-DBA function. Consequently, in a multi-tenancy context, the VNOs are not able to directly control the DBA process for ONUs associated with their customers/services, in other words, VNOs cannot schedule themselves the burst allocation of their customers' ONUs. Proper burst allocation by DBA is important to assure strict-QoS (in terms of jitter and latency), e.g., for low latency cloud-RAN and other Fifth Generation (5G) services. To assure strict-QoS services, the VNOs would have to request and rely on Service Level Agreement (SLA)'s guarantees (e.g., bandwidth, latency, jitter) to be provided by the InP, that would manage its DBA to combine the different offered services to the different VNOs. However, this would be rather static and might not be able to follow some VNOs requirements. For instance, the InP can assign a certain amount of assured band-



(a) Conventional PON (b) Multi-tenant PON with DBA Virtualization

Figure 3.2: Conventional PON vs. Proposed Multi-Service/Tenant PON

width to each VNO and guarantee their QoS requirments averaged over a few miliseconds. Alternatively, to enable direct control of each VNO on their own DBA process, we propose a multi-tenant architecture shown in Figure 3.2b. The description below reports the operation of layers that are involved in the vDBA process. The physical layer takes care of framing in the data plane; the Merging Engine (ME) layer receives multiple vDBA BMaps, merging them into one physical BMap for the ONUs; and the vDBA layers, operated by the VNOs compute a Virtual Bandwidth Map (vBMap) for each slice of OLT they have access to. The vDBA operates within a virtual OLT (vOLT), which is an Network Function Virtualization (NFV) slice of a physical OLT and is associated with a VNO. The vDBA allows VNOs to control, for each Transmission Container (T-CONT), upstream capacity, latency, and jitter in a shared physical OLT, thus delivering a *True Multi-Tenant PON solution*. The layers of the vDBA architecture are as follow:

- **Virtual OLT layer with vDBA**

  This is the layer controlled by the VNO, which enables full control over the choice of the most appropriate vDBA algorithm to run on the virtual PON slice. As shown in Figure 3.2b, the vDBA generates the vBMap for its PON slice and delivers it to the ME. For ONUs with strict latency and jitter requirements, this vBMap indicates the desired position for each slot allocation. In this way, the VNO obtains full control over the upstream capacity scheduling within each frame. The vDBA should create a vBMap based on the same frame size as the physical BMap.

- **Merging Engine (ME) Layer**

  The ME is the core of the multi-tenant PON architecture. It is considered the bridge between the OLT and vOLTs. The ME replaces the physical DBA layer and has two main tasks. Firstly, it relays queue status report messages (BufOcc or report frames) coming from the ONUs (from specific T-CONTs) towards the relevant vOLT. Secondly, it analyzes the vBMaps from all vDBAs, merging them into one physical bandwidth grant (PHY-BMap) and sends it to all ONUs. It should be noticed that for cloud-RAN, which has very strict latency and jitter constraints, but for which the BBU knows in advance the upstream capacity allocation, BufOcc (normally generated by the ONU) could be generated directly by the BBU, and sent to the vDBA, to eliminate the latency associated with the queue reporting mechanism [1, 8]. The ME is controlled by the InP. The ME should send PHY-BMap to all ONU every frame (e.g., every 125 microseconds). vDBAs however are not required to submit a vBMap every frame. It should be noted that in order to reduce the latency between the Transmission Convergence (TC) layer, ME, and vDBA, these might be physically co-located, for example in a system-on-chip architecture.

- **Transmission Convergence (TC) Layer**

  The TC layer implements the framing and other data plane functions. The InP is in charge of controlling this layer and will manage the different wavelength channels in a multi-wavelength PON.

3.3 Quality of Service Classes

There should be at least three classes of service for the T-CONTs in the vDBA scheme:

- Strict-QoS T-CONT, which defines latency and jitter constraints in addition to AIR-/PIR. The ME is required to consider the specific slot allocation (i.e., start and stop position of each allocation) only for this service class.
- QoS T-CONT which only define assured rate - AIR (which is met within the few milliseconds described in existing standards)

- Non-assured T-CONT, which is allocated capacity when there is space available.

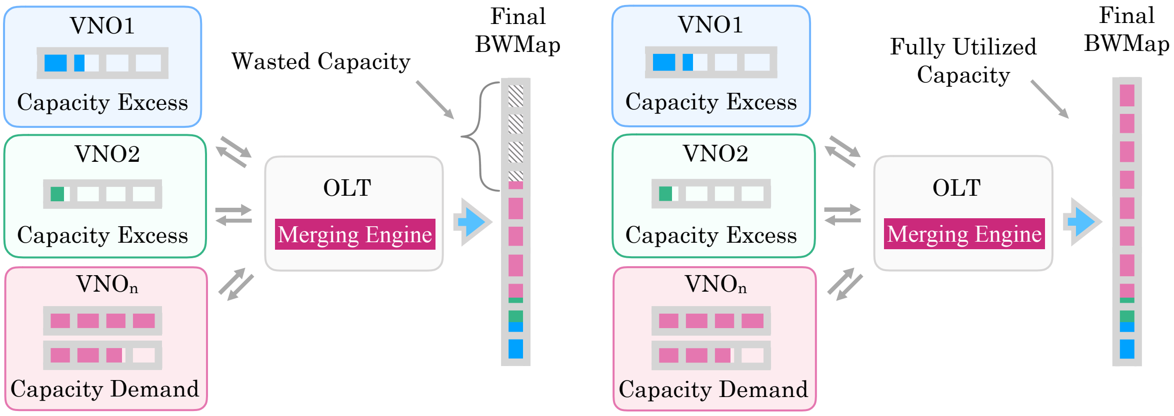
Whenever a new service with strict latency and jitter is requested from a customer to the VNO, it allocates a new dedicated strict-QoS T-CONT, where the desired level of latency, jitter, and availability are defined together with the capacity needed (e.g., in terms of committed rate). The vDBA sends the request to the ME, which can accept or reject it, depending on the available capacity. Where there is overlap between vBMaps from different VNOs, the ME can move the slots allocation when generating the physical BMap with respect to their request in the vBMap, as far as the allocated slots still respect the capacity and maximum latency and jitter required by the ONU. In the case where the service requiring the strict-QoS has a fixed transmission rate (or fixed within a given time length of several frames duration), there can be an additional negotiation phase during the initial allocation of the T-CONT, to mitigate the issue above. The vDBA can propose a slot allocation, which shall then remain constant across several other frames. The ME can either accept, reject, or propose modifications to the T-CONT allocation, e.g., in a way that would fit within the frame allocation (i.e., considering other similar services already allocated). The process will iterate until an agreement is reached or the service is rejected.

3.4 Inter-Operator Excess Capacity Sharing

The ME analyzes the vBMaps from all vDBAs, merging them into one physical BMap. Within the context of XGS-PON, the ME layer is responsible for merging vBMaps generated from virtual DBAs. Each VNO has been dedicated a pre-negotiated share of every frame which could utilize as it sees fit. However, in the case when one or more VNOs do not have enough demand for transmission from their ONUs, the excess capacity could be shared with other VNOs that potentially have excess demand for bandwidth.

To further investigate this, we have considered two merging policies:

- Excess Non-Sharing Policy: in this policy (depicted in Figure 3.3a), each vDBA shall produce a vBMap not exceeding their fixed dedicated share of the upstream frame: for example in the case of two VNOs, one could be allocated the first half of the upstream frame and the other the second half. The ME layer simply concatenates the vBMaps. This simple policy does not allow the unused capacity of one VNO to be shared with



(a) Excess Non-Sharing Policy (b) Excess Sharing Policy

Figure 3.3: Inter-Operator Excess Capacity Sharing Policies

the other VNOs.

- Excess Sharing Policy: in this policy (depicted in Figure 3.3b), each vDBA can act over the entire upstream frame, assigning capacity (assured, non-assured and best effort) up to the maximum amount that has been pre-negotiated with the PON InP. The ME layer will then merge the vBMaps from all VNOs according to the following conditions:
  - If all bandwidth grants can be accommodated, then no changes will be made to any of the vBMaps.
  - If some bandwidth grants cannot be accommodated, the bandwidth grants of overloaded VNOs are to be reduced in order to be fitted in the next upstream frame. To reduce bandwidth grants, the ME layer starts reducing best-effort traffic grants first. If still not enough, non-assured traffic bandwidth grants are also to be reduced. Assured capacity will always be allocated.

The performance evaluation of the proposed DBA virtualization is presented in [117]. The simulation results show that it is possible to realize DBA virtualization while not imposing considerable additional signaling delay to PON's capacity scheduling. The results also show that excess sharing policy has significantly superior network utilization (lower frame loss) compared to the excess non-sharing policy. Therefore the decision of the sharing policy could significantly improve the overall utilization of the network.

3.5 Conclusions

In this chapter we introduced the concept of DBA virtualization. The objective of vDBAs is to allow VNOs to implement their version of DBA autonomous from the InP. Our proposed virtualization of the DBA is included in the BBF TR-402 standard and been patented [123]. This allows different VNOs to implement their flavor of the DBA, providing them with the required flexibility to control the upstream scheduling, paving the way for the adoption of PONs as a primary transport network solution for new bandwidth-intensive services (5G, Virtual reality, etc.). In this chapter, we have addressed the possibility of providing the required control to the VNOs by dedicating virtual and programmable instances of the DBA algorithms. Therefore, each VNO will operate a portion of the network, and their bandwidth allocation decision (referred to as vBMap) is aggregated by the ME in the final BMap. Regarding the inter-operator excess capacity, two different approaches for the merging algorithm, namely excess sharing and excess non-sharing policies, have been studied with the excess sharing policy indicating significantly better results in terms of PON utilization. The reported results show that the sharing capacity approach can enable true multi-tenancy while not imposing any significant delay to the PON scheduling.

Giving VNOs the ability to schedule their entire capacity creates a new problem. If a VNO has leftover capacity on any given frame, it would have no gain in leaving this unallocated, as the ME would redistribute it to other VNOs which are likely to be its competitors. Thus its best strategy would always be to send a fully allocated vBMap to the ME. This constitutes a problem as it reduces the overall upstream PON efficiency. This challenge motivated the research question addressed in the next chapter of this dissertation, where we propose the monetization of the excess capacity of PON slices using an auction mechanism. We enable the VNOs to trade their excess capacity in return for monetary compensation. The proposed market-based approach provides the absent sharing incentive for the VNOs and assures high network utilization.

The experimental results have been omitted from this chapter to retain the originality of this dissertation as the experiments have been carried out by other co-authors (accessible in [117]). The author's contribution to this work includes developing the architecture for the DBA virtualization, the vDBAs' interaction with the OLT and the merging engine policy.

4 PON Sharing Market Mechanism

PON Sharing Market Mechanism

> *"The Best for the group comes when everyone in the group does what's best for himself and the group."*
>
> —John Forbes Nash Jr.

In chapter 3 we introduced a new Passive Optical Network (PON) sharing approach where multiple Virtual Network Operators (VNOs), each providing a different service, can coexist on the same PONs network while running a virtual instance of the Dynamic Bandwidth Allocation (DBA) algorithm of their choice and aggregating these scheduling decisions into a final Bandwidth Map (BMap). Two methods for dealing with the excess bandwidth of the VNOs namely *Sharing* and *Non-Sharing* were analyzed with the conclusion that the sharing method considerably improves the utilization of the network. Nevertheless, chapter 3 overlooks the incentives of the VNOs to share their excess bandwidth with other VNO's while it can blindly allocate the bandwidth to its own users' unpredictable demand surge. In situations that the participants lack incentives for sharing a resource, *monetization* (i.e., monetary compensation) comes to the help as a manifest tool to incentivize self-interested agents to engage in sharing (e.g., ride-sharing and Airbnb). The same tool can be used to address the incentive problem in multi-tenant PONs. Where the VNOs are compensated by money/credit in return for sharing their excess capacity with others. The VNOs in demand of extra capacity will report their valuations while on the other side the VNOs who own this extra capacity will announce their valuation and then simply, the demander with the highest valuation gets the capacity from the supplier with the lowest. Though, this is an unrealistic over-simplification of the allocation as this solution will in many ways allow the VNOs to strategize and take advantage of this design flaw and improve their payoff by damaging the others'. In this chapter, we will study the potential design flaws associated with such a market and will try to build a mechanism to minimize or entirely solve them. In the following section we propose a network model for the inter-operator excess capacity sharing in PONs and introduce the market players and elements along with the monetary interactions among them.

4.1 Market Model

In this section, we present a market model (depicted in Figure 4.1) for the multi-tenant PONs' excess capacity market. We first introduce the market players and the preliminaries while defining the essential parameters and features of the market. Next, we point out the desired economic properties of the market and define the utility function of the market players.

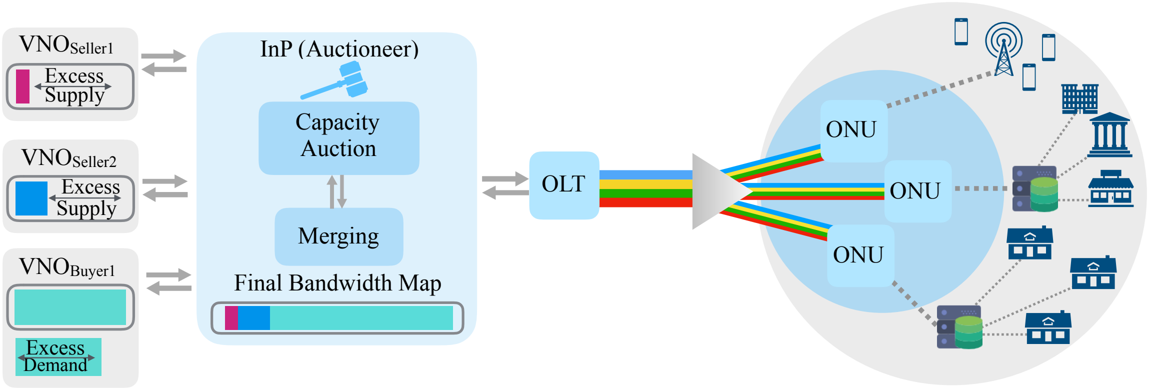


Figure 4.1: The Multi-Tenant PONs Network Model

4.1.1 Preliminaries

The market consists of a set of M sellers $\mathbb{S} = \{s_1, s_2, ..., s_i\},\ i \in M$ and a set of N buyers $\mathbb{B} = \{b_1, b_2, ..., b_j\},\ j \in N$ and one auctioneer. This constructs a two-sided market in which a number of traders are competing to trade identical items in a way that it will maximize their payoff. There is also an auction maker (broker) present that is responsible for operating the auction. In our market, the Infrastructure Provider (InP) plays the role of the auctioneer.

The auctioneer initiates the auction. Each seller announces the quantity of the items offered q_i^S along with the per-item ask value v_i^S to the auctioneer. Simultaneously the buyers will send their pair of the number of items required q_j^B and the bid value v_j^B to the auctioneer. The ask and bid values (v_i^S, v_j^B) are $\in [0,\ 1]$. The auction mechanism is common knowledge.

Definition 1. **VNOs' Per-Item Valuation**

Table 4.1: Market Model Parameters

Parameter	Descriptions
S_i	i^{th} Seller
B_j	j^{th} Buyer
v_i^{S}	Per-item ask value of i^{th} seller
v_j^{B}	Per-item bid value of j^{th} buyer
q_i^{S}	Quantity of the items offered by i^{th} seller
q_j^{B}	Quantity of the items demanded by j^{th} buyer
θ_i^{S}	Quantity of the items sold by i^{th} seller
θ_j^{B}	Quantity of the items bought by j^{th} buyer
$\Theta_{\mathrm{P}r}$	Total No. items traded using the proposed mechanism
Θ_{XU}	Total No. items traded using the Xu et al. mechanism
p^{S}	Sellers' trade price
p^{B}	Buyers' trade price
u_i^{S}	Trade utility of i^{th} seller
u_j^{B}	Trade utility of j^{th} buyer
$u^{\mathrm{A}uc}$	Trade utility of the auctioneer

The valuation of a VNO for an item is driven by its probability of being able to utilize it. This valuation thus ranges between [0,1], $p = 0$ for definitely not having any user asking for any bandwidth. $p \in (0, 1)$ for having a probability between 0 and 1 that a new upstream burst arrives in one of the users' buffer since the last time that the buffer occupancy was reported (this might be predicted using machine learning or traffic history monitoring techniques). And $p = 1$ for definite demand from the users that in PONs is referred to as *"buffer occupancy reports"*. For instance, if a VNO reports a quantity of 1000 items and its preassigned provisioned share is 900 items, it means that it will certainly utilize the 900 items with the probability of 1 and is demanding for 100 extra items and there is a probability of v_j that it will utilize the excess items.

The market model parameters are summarized in Table. 4.1. Each seller $S_i (i \in I)$ is willing to supply q_i^S items for the minimum price of v_i^S. On the other side of the market each buyer $B_j (j \in J)$ is willing to buy q_j^B items and is willing to pay v_j^B for each item at most.

When the auction has ended, the winning sellers will each receive $p^{\mathrm{S}} \times \theta_i^{\mathrm{S}}$ and the winning buyers will pay $p^{\mathrm{B}} \times \theta_j^{\mathrm{B}}$ where the p^{S} and p^{B} are the buyers' and the sellers' trade price and θ_i^{S} and θ_j^{B} are the quantity of the items traded for the buyers and the sellers respectively. By our design the traders can be partially satisfied that is they can sell/buy $\theta_i^S \leq q_i^S$ or $\theta_j^B \leq q_j^B$.

Definition 2. **Strategy**

In the context of our market the only effects that a trader can have on the market, and the final allocation are its reported value and quantity. Thus a trader's strategy is the value and quantity pair that it reports to the auctioneer.

A trader can either report its true or a manipulated value which to elaborate further; it can follow a function that maximizes its payoff. All the traders are driven by their payoffs; this current practice may also endanger the market maker's revenue in the long run.

The quantity of items sold/bought by each seller/buyer is shown as θ_i^S, θ_j^B respectively. The total number of items traded in the auction (Θ) is calculated as follows:

$$\Theta = \sum_{i=1}^{M} \theta_i^S = \sum_{j=1}^{N} \theta_j^B \tag{4.1}$$

Where M and N are the number of Sellers and buyers respectively.

Utility (Payoff)

The utility of a seller (u_i^{S}) is the difference between the total amount paid to them in return for the sold items and their true valuation times the number of items sold (Θ_i^{S}):

$$u_i^{\mathrm{S}} = \theta_i^{\mathrm{S}} \times (p^{\mathrm{S}} - v_i^{\mathrm{S}}) \tag{4.2}$$

The utility of a Buyer (u_j^{B}) represents the difference between its true valuation for all the acquired items and the its total payment times the number of items acquired (Θ_j^{B}):

$$u_j^{\mathrm{B}} = \theta_j^{\mathrm{B}} \times (v_j^{\mathrm{B}} - p^{\mathrm{B}}) \tag{4.3}$$

The utility of the auctioneer is the budget surplus which is the difference between the amount paid by the buyers and the amount to be paid to the sellers:

$$u^{Auc} = (p^{\mathrm{B}} \times \sum_{i=1}^{M} \theta_i^S) - (p^{\mathrm{S}} \times \sum_{j=1}^{N} \theta_j^B) \tag{4.4}$$

and since according to Eq.4.1

$$\Theta = \sum_{i=1}^{M} \theta_i^S = \sum_{j=1}^{N} \theta_j^B$$

Hence:

$$u^{Auc} = (p^{\mathrm{B}} - p^{\mathrm{S}}) \times \Theta \tag{4.5}$$

In the next section we propose an auction mechanism that determines the quantity and the price of trade for each trader in a way that first, it requires minimal communication among the traders and the auctioneer while second, it achieves higher or at worst the same social welfare for the market.

4.2 McAfee-Based Double Auction Mechanism

We propose a sealed-bid homogeneous item double auction mechanism to determine the winners and setting the trading prices. In a sealed-bid auction all traders simultaneously submit sealed asks/bids to the auctioneer, and no trader is aware of the ask/bid of any other participant. An auction is a homogeneous item when the trading items are identical; thus the traders have no preferences over any of the items.

The mechanism provides a matching service to multiple buyers and sellers in a bilateral trade environment. We assume rational traders whose effort is focused on maximizing their payoff by trading the identical items. A market maker, or the auctioneer, is responsible for operating this market and conducting the auctions while having no or incomplete information about the true valuations of the traders. There is a finite number of alternative resource allocation combinations. Each combination would bring a different individual and social payoff for each trader and the entire market. We chose a sealed-bid auction due to the latency constraints in PON networks and the fact that we need to run the auction in microseconds time scales, we cannot afford multiple rounds of communication among the sellers, auctioneer and the buyers. Therefore, we have to minimize these communications. Using the sealed-bid version of auction helps us to eliminate the need for any additional round of communication among the agents as the traders only send the ask/bid values once along with their BMap (the suggested allocation schedule). The algorithmic representation of the proposed double auction mechanism is given in algorithm 1.

Algorithm 1: Multi-Item Double Auction

```
Sort sellers ascending so $v_1^B > v_2^B > ... > v_m^B$
Sort buyers descending so $v_1^S < v_2^S < ... < v_n^S$
Find $max(S_L, B_K)\ \forall\ v_L < v_K$ and $\sum_1^{K} q_j^B \leq \sum_1^{L} q_i^S$
$\gamma = \frac{1}{2} \times (v_{L+1} + v_{K+1})$
if $\gamma \in [v_L, v_K]$ then
    $\Theta_{Pr} = \min(\sum_1^{i=L} q_i, \sum_1^{j=K} q_j)$
    $p^B = p^S = \gamma$
else if $\gamma \notin [v_L, v_K]$ then
    $\Theta_{Pr} = \min(\sum_1^{i=L-1} q_i, \sum_1^{j=K-1} q_j)$
    $p^B = v_K$
    $p^S = v_L$
```

We assume that there are no restrictions on the sets of buyers and sellers that may trade with one another nor any preferences over trade between any of the traders. The steps of the proposed auction mechanism are as follow:

1. The auctioneer sorts all the buyers (based on their ask/bid value) so that:

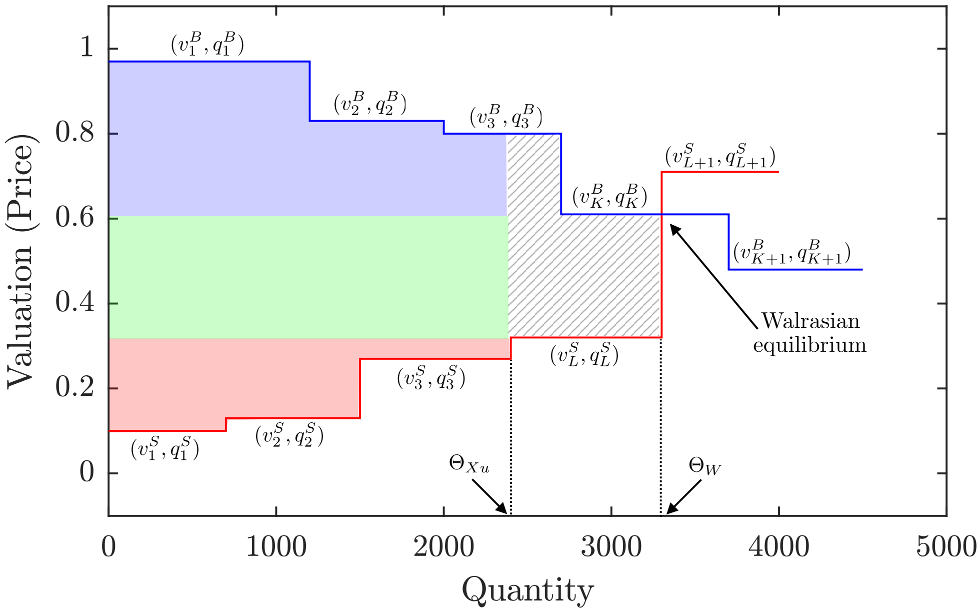
$$\{\tilde{\mathbf{S}} = \{s_1, s_2, ..., s_i\} : v_1^S < v_2^S < ... < v_n^S\} \tag{4.6}$$

   and

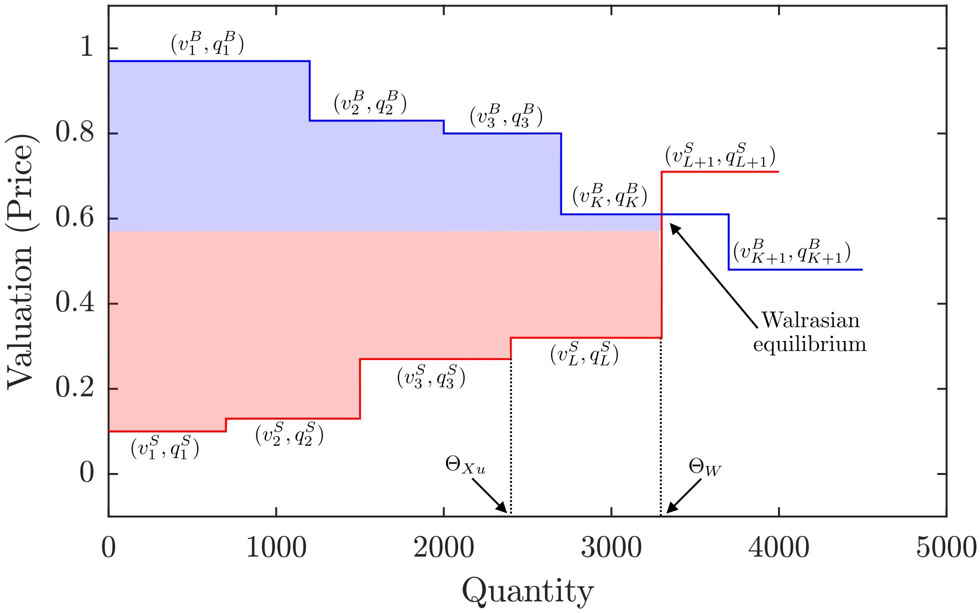
$$\{\tilde{\mathbf{B}} = \{b_1, b_2, ..., b_j\} : v_1^B > v_2^B > ... > v_m^B\} \tag{4.7}$$

   Equation 4.6 shows the sellers arranged in an ascending order and Equation 4.7 shows the buyers sorted in a descending order by the value of their v.

2. The auctioneer discovers the Walrasian equilibrium quantity as shown in Figure 4.2 as Θ_{W}. Figure 4.2b depicts the discrete supply and demand graph for one instance of the proposed auction (one round of the auction for one frame of the PON upstream transmission) representing the trades' valuation and quantity. In Figure 4.2 each step in the red line represents a seller, and each step in the blue line represents a buyer. In this example there are five sellers and five buyers in the market and $\gamma \in [v_L, v_K]$. As shown in Figure 4.2a, the gray area, representing the trading utility, is sacrificed



(a) *Xu et al. [101]* Double Auction



(b) Proposed Double Auction

Figure 4.2: Discrete Supply-Demand Graph of the Double Auction

to achieve truthfulness. In contrast, our proposed trade reduction technique depicted in Figure 4.2b saves this amount of wasted utility while maintaining the truthfulness. In Figure 4.2a, the blue, green and red area represent buyers', auctioneer's and the sellers' utility from the auction, respectively. As it can be seen in Figure 4.2b, for this particular instance of the market our proposed mechanism brings zero utility for the auctioneer. In general however, the auctioneer's overall utility will be the surplus between the buyers' payment and the sellers' receivables goes to the auctioneer (zero when $\gamma \in [v_L, v_K]$ and $(p^{\mathrm{B}} - p^{\mathrm{S}}) \times \Theta$ when $\gamma \notin [v_L, v_K]$).

Definition 3. **Walrasian (Competitive) Equilibrium**

In the context of our double auction market, the *Walrasian Equilibrium* is the point in the supply-demand plot (Figure 4.2) in which the supply equals the demand. This point specifies the maximum quantity of feasible trades in which the sellers' price is less than the buyers' price. In other words, this is the *upper-bound* of market allocation efficiency.

The Walrasian equilibrium defines another important factor, the *Walrasian Price* in which if the trade is conducted brings positive payoff for both the supplier and the demander and also balances the budget, i.e., it determines the biggest (L, K) in which:

$$v_K^B \geq v_L^S \text{ and } v_{K+1}^B \leq v_{L+1}^S, \tag{4.8}$$

and

$$\sum_{j=1}^{\mathrm{K}} q_j^B \leq \sum_{i=1}^{\mathrm{L}} q_i^S. \tag{4.9}$$

We refer to the last trading seller and buyer in the walrasian equilibrium as S_L, B_K, respectively. The Walrasian equilibrium realizes the *Pareto efficiency.* A resource allocation decision is referred to as Pareto efficient if it is impossible to reallocate the resources in a way that makes one of the agents better off without making others worse. This quality makes the Walrasian allocation a suitable benchmark of efficiency in economic analysis.

3. To achieve dominant strategy truthful value-reporting we have to decouple the trade price of the sellers and buyers from their reported value. This is achievable through *Trade Reduction.*

Definition 4. **Trade Reduction**

A technique in which the least efficient trade in the market is sacrificed so the other traders can trade on their reported value, thus their reported valuation does not affect their payments, i.e., they have no incentive to report untruthful values (leading to Incentive Compatibility (IC)).

Thus, q_r trades will be removed from the market. In Figure 4.2a the reduced area is shown in gray. Obviously, it is possible that by removing q_r trades from the market we may have to eliminate more than two traders (completely or partially) from the

Table 4.2: One Instance of the Double Auction Market.

Sellers	700@0.10	800@0.13	900@0.27	900@0.32	700@0.71
Buyers	1200@0.97	800@0.83	700@0.80	1000@0.61	800@0.48

(a) Sellers and buyers and their quantity to sell/buy@ask/bid price

Sellers	700@0.32	800@0.32	900@0.32	0	0
Buyers	1200@0.61	800@0.61	400@0.61	0	0
					$\Theta = 2400$

(b) Sellers and buyers and $\theta_i^S/\theta_j^B@p^S/p^B$ Xu et al. mechanism

Sellers	700@0.595	800@0.595	900@0.595	900@0.595	0
Buyers	1200@0.595	800@0.595	700@0.595	600@0.595	0
					$\Theta = 3300$

(c) Sellers and buyers and $\theta_i^S/\theta_j^B@p^S/p^B$ proposed mechanism

market.

In our proposed mechanism, the total number of items sold by the sellers, which is equal to the total number of items bought, by the buyers is represented as Θ_{Pr}. The value of Θ_{Pr} directly affects the link utilization of the PONs.

$$\Theta_{Pr} = \min(\sum_{i=1}^{L} q_i, \sum_{j=1}^{K} q_j) \tag{4.10}$$

The quantity of reduced trades is defined as q_R:

$$q_R = \Theta_W - \Theta_{Pr} \tag{4.11}$$

The amount of efficiency (utility) sacrificed in the market due to this trade reduction is:

$$\textit{Efficiency loss} = q_R \times (v_K - v_L) \tag{4.12}$$

Table 4.2a presents the numerical information (the traders' preferences) used in Figure 4.2a and the different market results using the auction mechanism introduced by *Xu et al.* [101] (in Table 4.2b) and the results from the proposed mechanism in Table 4.2c. Our contribution in this chapter is to propose a trade reduction technique that minimizes q_R without loosing the economic properties. We improve the technique used in [96] which uses the values of S_{L+1} (the strongest non-trading seller) and B_{K+1} (the strongest non-trading buyer) to determine the traders' payment if and only if:

$$\gamma = \frac{1}{2} \times (v^S_{L+1} + v^B_{K+1}) \in [v^S_i, v^B_j] \tag{4.13}$$

thus since v^S_L, v^B_K, and in general none of the trading players, do not play a role in the price determination, i.e., there is no need to eliminate any of the traders including S_L and B_K from the market, therefore $q_R = 0$. In this case the sellers and the buyers both trade in $\gamma = p^S = p^B$.

Definition 5. Weakest/Strongest Trader: In the context of market power, the weakest traders are the seller with the highest asking price v^S_i and the buyer with the lowest bid v^B_j. On the other side, strongest traders are the seller with the lowest ask and the buyer with the highest bid.

In Figure 4.2a the blue area is the sellers' utility, the green area is the auctioneer's and the red is the buyers'. The gray area is the amount of lost efficiency, e.g., when the trade reduction is applied.

4.3 Market Evaluation Methodology

In this section, we first define the criteria for economic robustness that is achieved by fulfilling a number of economic properties. Next, we introduce the methods used to confirm the economic robustness of the proposed market mechanism, including theoretical proof and game trees. Finally, using market simulations, we illustrate the performance of the proposed model in terms of bandwidth utilization and market social welfare.

4.3.1 Economic Properties (Economic-Robustness)

The four essential principles of a desirable auction mechanism design includes optimal Allocative Efficiency (AE), IC, Individual Rationality (IR) and Budget Balance (BB) [124].

1. **Optimal Allocative Efficiency (AE):** The outcome allocation of the items maximizes the social welfare (i.e., the aggregate of all participants' utilities).
2. **Incentive Compatibility (IC):** An auction mechanism is IC when reporting the true valuation is a dominant strategy for all the traders, i.e., no trader can improve its

utility gain from the market by reporting an untruthful value. This is also referred to as *Truthfulness* and *Strategyproofness* in the literature.

Definition 6. Dominant strategy: In game theory, a strategy is dominant for a player if regardless of what other players do, there is no alternative strategy to be played that will bring more utility to the player.

IC provides strong participation incentives for the traders by reducing the participation cost. The reasons to eliminate strategic behavior from the market are as follows:

(a) Strategic behavior of the traders makes the market very complicated to analyze. Especially for a market such as double-auction multi-item market in which there is competition both between the same type of the traders (i.e., seller/seller or buyer/buyer) and opposing type of traders (i.e., seller/buyer) and there is an incentive for them to strategize through untruthful value/quantity reporting to achieve a higher utility.

(b) Strategic behavior can impose a substantial social cost on the market as it promotes competitive strategizing. The traders would spend resources to acquire more information about the market and their competitors' preferences, and this consequently will negatively affect their market power, i.e., asks/bids.

3. **Individual Rationality (IR):** All traders have non-negative utility if they participate in the market.
4. **Weak Budget Balance (BB):** The auctioneer does not run at a negative utility. A mechanism is referred to as weakly budget-balanced if the auctioneer does not get a negative utility. Still, it may have a positive utility. Our desired mechanism is weakly budget-balanced as the auctioneer will get the market surplus as its operation fee.

4.3.2 Theoretical Proofs

Considering that the number of cases is finite and limited, we have used the *Proof by Exhaustion* method to confirm the satisfaction of the desired economic properties. We conduct a case analysis to study every possible outcome of the market players' strategic behavior. This is to assure that none of the market players could use manipulative techniques to undermine the market and achieve higher profits from it. Such manipulative techniques might include artificial intelligence assisted bidding strategies that could lead to further challenges. For fur-

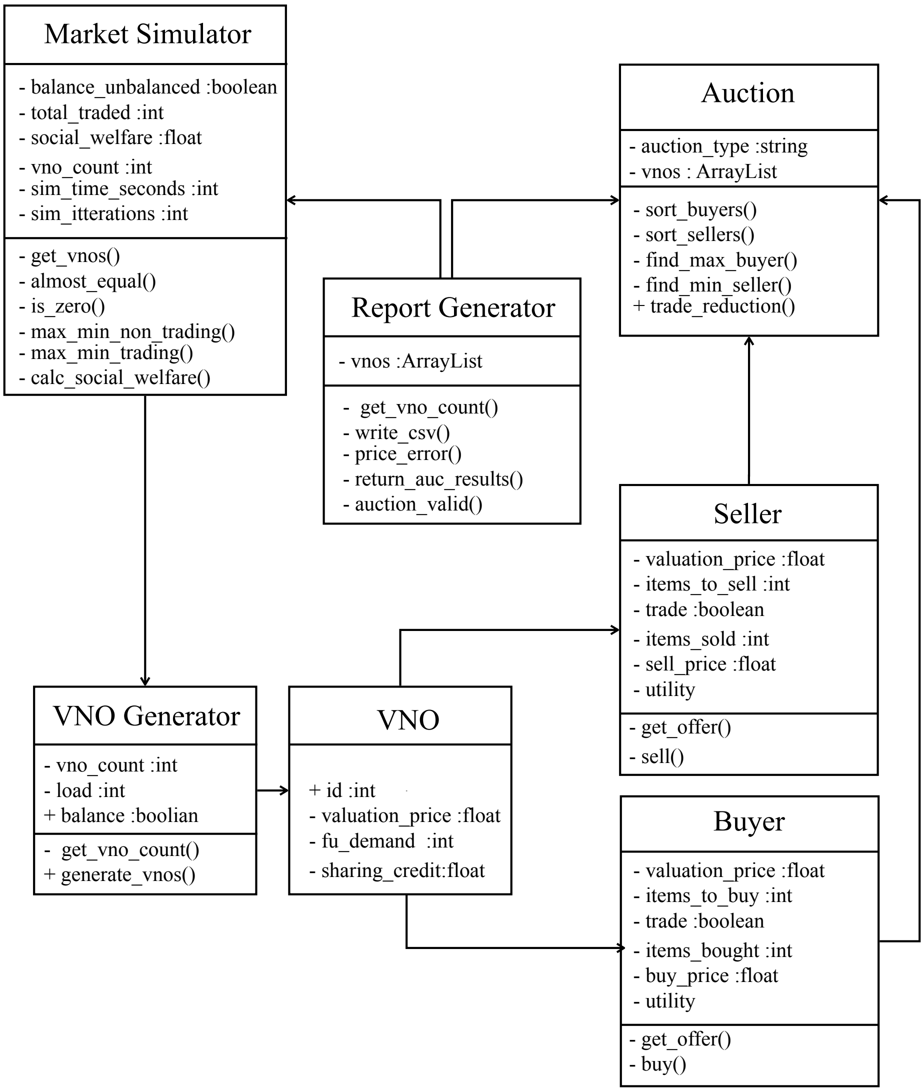


Figure 4.3: High Level Class Diagram of the Market Simulator

ther clarification, we use game trees to represent the theoretical proofs visually. Game trees offer a visual alternative to illustrate the case by case outcome of the players' strategy in the game.

4.3.3 Market Simulation

While theoretical proofs can be used to assure satisfying IC, BB, and IR, however, to test and evaluate Allocative Efficiency, it is necessary to observe the market and gather information on specific parameters. This information is then used to compare the efficiency of the market mechanism proposed in this dissertation with the state-of-the-art. Therefore we have developed a market simulation tool that gathers relevant parameters that are necessary for investigating the market performance. The market simulator can support various auction mechanisms and generate results on the following factors:

- Market Utility Distribution: The share of sellers/buyers from the market.
- Social welfare: The aggregate utility of all the market participants.
- Network utilization: Bandwidth utilization of the PON.

The above factors (further introduced in section 4.5) extracted from the market simulations will allow comparative analysis between different market mechanisms (i.e., auctions). The market simulator is written in Python [125] programming language. A high-level class diagram of the market simulator is depicted in Figure 4.3. At the beginning of the simulation, the market simulator invokes a request from the *VNO generator* to generate the VNOs with the given number of VNOs and the load distribution. The generated VNOs are then categorized into sellers and buyers depending on their demand/excess, and the bid/asks are sent to the auction mechanism (see section 4.2). Finally, the *Report Generator* produces the results and returns them to the simulator. The simulations were undertaken using the CONNECT01 server available to Trinity College Dublin researchers. CONNECT01 is equipped with 44 processors with 64-bit architecture and uses Scientific Linux 6x [126] as its operating system. Further network-level simulation details are available in section 4.5.

4.4 Theoretical Proofs

4.4.1 Incentive Compatibility

We have to prove that no trader can achieve higher utility by reporting a manipulated value which can be determined by market monitoring techniques and prediction tools such as machine learning etc.

Lemma 1. No buyer can win more items by reporting an untruthfully lower value i.e., $\{\forall\, v'_j < v_j | \theta'_j \leq \theta_j\}$.

Proof. The value of the θ'_j depends on whether if the v'_j changes the position of B_j in the sorted buyers' list.

Case 1.a If B_j reports a $v'_j < v_j$ and by doing so its position in the sorted buyers list does not change then by design the outcome of the auction remains the same. Therefore, the quantity will not change i.e., $(\theta'_j = \theta_j)$.

Case 1.b If the reported v'_j changes the position of the buyer in the sorted buyers list, since its position will be downgraded the θ'_j at best case (e.g., if $j \leq k$) will be equal to θ_j and in the worst case (e.g., if $j = k+1$) zero i.e., $\theta'_j \leq \theta_j$.

Thus we have proven that if B_j reports an untruthful bid $v'_j < v_j$ it cannot increase its trade quantity, i.e., $\nexists\ {v'}^B_j < v^B_j \rightarrow (\theta'_j \leq \theta_j)$.

□

The game tree for this proof is depicted in Figure 4.4.

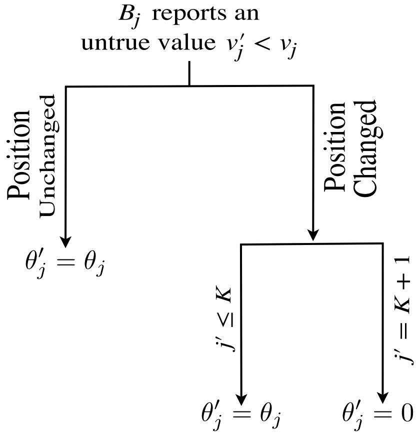


Figure 4.4: The Proof Tree for Lemma 1

Lemma 2. No buyer can decrease its per-item payment value by reporting an untruthfully lower value i.e., $\{\forall\ v'_j < v_j | p'_j \geq p_j\}$.

Proof. Lets consider that B_j reports an untruthful bid $v'_j < v_j$.

Case 2.a If the new v'_j does not change the position of B_j in the sorted buyers' list then the auction outcome remains unchanged, i.e., $p'_j = p_j$.

Case 2.b If the new v'_j does change the position of B_j in the sorted buyers' list, the following cases can occur:

Case 2.b.1 If the new $j' < K$ then the p remains unchanged, i.e., $p'_j = p_j$.

Case 2.b.2 If $j' = K$ and $\gamma \in [v_L, v_K]$ then again p'_j remains unchanged as it is equal to γ which is independent of the v'_j, i.e., $p'_j = p_j$.

Case 2.b.3 If $j' = K$ and $\gamma \notin [v_L, v_K]$ then B'_j does not win any items, i.e., $p'_j = 0$.

Case 2.b.4 Finally if $j' > K$ then B'_j does not win any items, i.e., $p'_j = 0$.

Thus we have proven that if B_j reports an untruthful bid $v'_j < v_j$ it cannot lower its trade price, i.e., $\nexists\ v'^{B}_j < v^B_j \rightarrow (p'_j \leq p_j)$. □

The game tree for this proof is depicted in Figure 4.5.

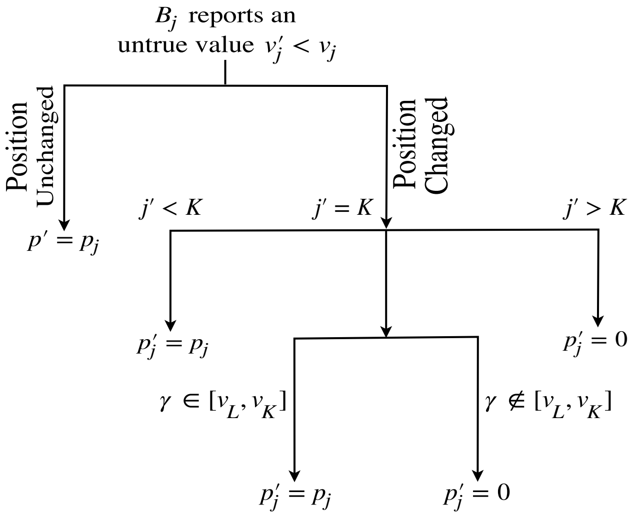


Figure 4.5: The Proof Tree for Lemma 2

Theorem 1. **Bid Independence:** There is no $v'^{B}_j < v^B_j$ which B_j can report and by doing so gain more utility $(u'_j \leq u_j)$ given that all the other players' bids and asks remain unchanged, i.e., $\nexists\ v'^{B}_j < v^B_j \rightarrow (u'_j \leq u_j)$.

Proof. According to Equation 4.3 the utility of a buyer only increases if the quantity of trade increases or the price to pay decreases or both. By proving lemma 1 and lemma 2 we have proven that there is no way for any buyer to manipulate the market by reporting a lower value than its true valuation and gain higher utility by doing so, i.e., $\{\forall\ v'_j < v_j | u'_j \leq u_j\}$. Thus the final utility of a buyer is independent from the bid that it submits if not higher. □

Corollary 1. According to theorem 1, the final utility is independent of the submitted bid. Thus it is a weakly dominant strategy for every buyer to report their true value and have a higher chance at winning since at worst the utility of truthful reporting is equal to that of a shaded (manipulated) bid.

Corollary 2. The dominant strategy truthfulness for the sellers can be proven in the same way as of Corollary 1.

4.4.2 Individual Rationality

Theorem 2. The proposed mechanism satisfies all traders' individual rationality.

Proof. The proposed mechanism is IR since by design it will not sell (buy) any item unless the trade price is higher (lower) than the seller's (buyer's) reported value. We assume that the VNOs are rational entities and would not report smaller values than their true value if they are sellers or bigger values than their true value if they are buyers. ☐

4.4.3 Weak Budget Balance

Theorem 3. The proposed mechanism is Budget Balance (BB).

Proof. The suggested theorem is invalid if and only if it is possible for the auctioneer to run a budget deficit. We will show that our mechanism does not allow that to happen. According to Equation 4.4 to get a negative u_{Auc} the following relationship must hold:

$$(p^{\text{B}} \times \sum_{1}^{n} \theta_j^{\text{B}}) < (p^{\text{S}} \times \sum_{1}^{m} \theta_i^{\text{S}})$$

that equivalently leads to the following inequality:

$$\frac{p^{\text{B}}}{p^{\text{S}}} < \frac{\sum_1^n \theta_j^{\text{B}}}{\sum_1^m \theta_i^{\text{S}}}$$

We know from the mechanism that $\sum_1^n \theta_j^{\text{B}} = \sum_1^m \theta_i^{\text{S}} = \Theta$, i.e., the total number of sold items is equal to the total number of items bought. Thus:

$$\frac{p^{\text{B}}}{p^{\text{S}}} < 1$$ ☐

According to our proposed mechanism, the buyers' trade price is always higher than the sellers' trade price, i.e., $p^{\text{B}} > p^{\text{S}}$. Therefore, the above inequality does not hold since it is in contradiction with the fact that $p^{\text{B}} > p^{\text{S}}$. Thus, we have proven that the u_{Auc} can never be negative.

4.5 Experimental Results

This section is dedicated to evaluating and analyzing the AE of the proposed mechanism and comparing it to prior work. We measure the AE by two factors:

1. The total number of items traded in one round of the auction (Equation 4.1). This factor directly determines the proportion of the PONs bandwidth that is being shared among the VNOs. Thus it can clearly reflect the effect of auctioning the capacity on the PONs's efficiency.

   To compare the results of different mechanisms we use the Walrasian equilibrium trade quantity as a baseline (upper-bound) since this is the maximum number of rational trades in the market. The closer the results are to the upper-bound the better. A rational trade is a trade in which the buyer's bid is strictly higher than the sellers, and the supply quantity is larger or smaller than the demand quantity.

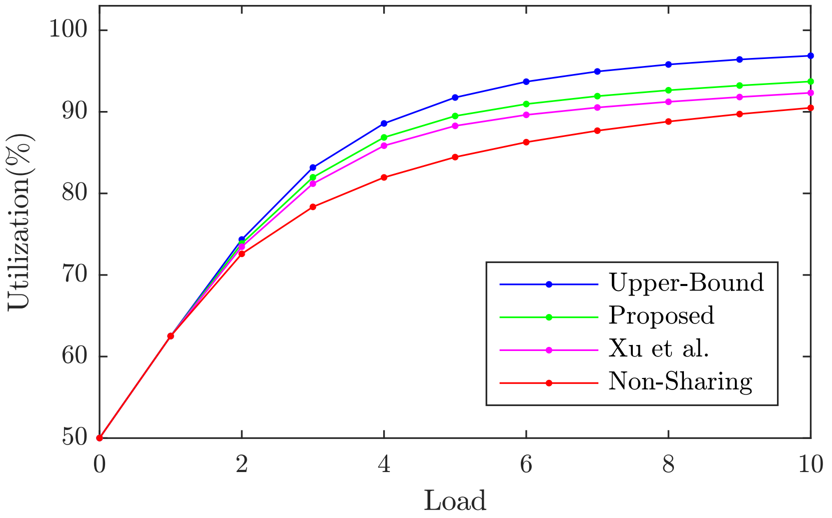
2. The Social Welfare, which is a factor representing the aggregate benefit brought to all the parties involved in the market. The social welfare is calculated by summing the utilities of the trading traders and the auctioneer in every round of the auction. The social welfare can clarify whether the mechanism has been successful in redistributing the bandwidth from the sellers who value the items the least to the buyers with the highest valuation and therefore maximizing the total profit generated by the market. The Social Welfare is calculated as follows:

   $$SW = \sum_{i=1}^{i=L} u_i^S + \sum_{j=1}^{j=K} u_j^B + u_{Auc} \tag{4.14}$$

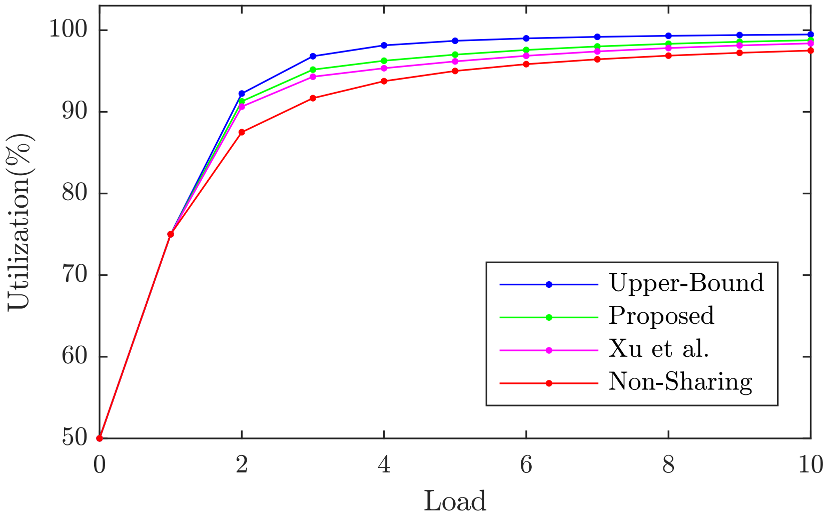
   In which the SW is the social welfare of the system in each round of the auction.

We consider an XGS-PON [119] with 10 Gbit/s (nominal line rate of 9.95328 Gbit/s symmetrical capacity). We simulate a market with ten VNOs each with an equal share of the upstream bandwidth, i.e., 995.328 Mbit/s≈1-Gbit/s. This translates to 972 blocks (one block is 16 bytes as defined in the standard [119] as the finest granularity for upstream allocation) or blocks per frame (125 μs) per VNO. Each VNO will ask for a number of blocks depending on its users' instantaneous demand. This number determines that if the VNO is a seller (if asking for a lower than the pre-defined share), a buyer (if asking for higher) or a non-trader (if asking for the exact same amount).

In the rest of this section, we report the market simulation results regarding Market Utility Distribution, Network utilization, and the Social welfare (see subsection 4.3.3).



(a) Unbalanced Load



(b) Balanced Load

Figure 4.6: Simulation results of our DBA auctions, showing how the auction mechanism increases PONs utilization.

Network Utilization

Figure 4.6 illustrates the performance comparison of the proposed mechanism with non-sharing and *Xu et al.* [101] mechanism. The *"Upper-Bound"* is the maximum reachable utilization while overlooking the economic properties. As we mentioned in the previous sections "*Xu et al.*" is a mechanism that works similar to our proposed mechanism with a difference that its trade reduction mechanism always removes S_L, B_K. The *"Non-sharing"* represents the approach where VNOs do not share their excess capacity with others (i.e., no auction happens, and all the excess capacity is wasted).

Figure 4.6a and Figure 4.6b depict the utilization (averaged over the simulation time) of

Table 4.3: Unbalanced Load Utilization

Load	Non-Sharing	*Xu et al.*	Proposed	Upper-Bound
1	75.01	75.01	75.01	75.01
2	87.51	90.64	91.28	92.24
4	93.75	95.34	96.26	98.14
6	95.84	96.86	97.58	99.00
8	96.88	97.81	98.33	99.31
10	97.51	98.38	98.77	99.47

Table 4.4: Balanced Load Utilization

Load	Non-Sharing	*Xu et al.*	Proposed	Upper-Bound
1	62.51	62.51	62.51	62.51
2	72.59	73.46	73.86	74.35
4	81.96	85.85	86.86	88.58
6	86.28	89.63	90.96	93.70
8	88.81	91.23	92.65	95.80
10	90.49	92.33	93.72	96.88

each mechanism in the unbalanced (randomly weighted load) and balanced (equally weighted load) network loads respectively. Intuitively, the *"Upper-Bound"* achieves the highest utilization as it ignores the truthfulness and puts a naive trust on the VNOs to report their values truthfully, thus does not remove any trades from the market. However, this is not acceptable since in such conditions the traders do not have any incentive to report true values and will potentially try to manipulate the market by reporting untrue values. This may lead to a situation where no trader gets to trade since they all are greedily trying to maximize their own utility without considering the others' welfare, e.g., ask prices are too high and bids are too low, so no trade happens. The horizontal axis in Figure 4.6 represents the average incoming load of each VNO, and the vertical axis shows the utilization of each mechanism in a given load.

The numerical results of the simulation are given in Table 4.3 and Table 4.4. According to our results, in both balanced and unbalanced load, the proposed mechanism outperforms *Xu et al.* mechanism as its trade reduction technique allows more trades to be conducted.

Market Utility Distribution

The utility (profit) function of the sellers, buyers and the InP are defined as u_i^{S}, u_j^{B}, and u^{Auc}. The utility of a seller (u_i^{S}) is the difference between the per-item selling price and the asking price of that seller, times the number of items sold θ_i^{S}:

$$u_i^{\mathrm{S}} = \theta_i^{\mathrm{S}} \times (p^{\mathrm{S}} - v_i^{\mathrm{S}}) \tag{4.15}$$

Similarly for the buyers:

$$u_j^{\mathrm{B}} = \theta_j^{\mathrm{B}} \times (v_j^{\mathrm{B}} - p^{\mathrm{B}}) \tag{4.16}$$

The utility of the auctioneer is the difference between the amount paid by the buyers and the amount to be paid to the sellers:

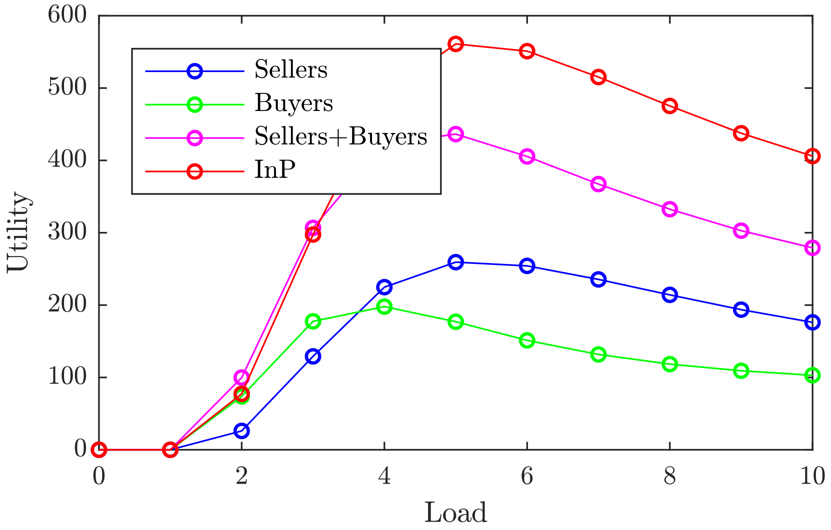
$$u^{Auc} = (p^{\mathrm{B}} - p^{\mathrm{S}}) \times \Theta \tag{4.17}$$

Where θ_i^{S} is the items sold by the i^{th} seller for the price of p^{S}, θ_j^{B} is the items won by the j^{th} buyer with the price of p^{B}, and Θ is the total number of items traded.

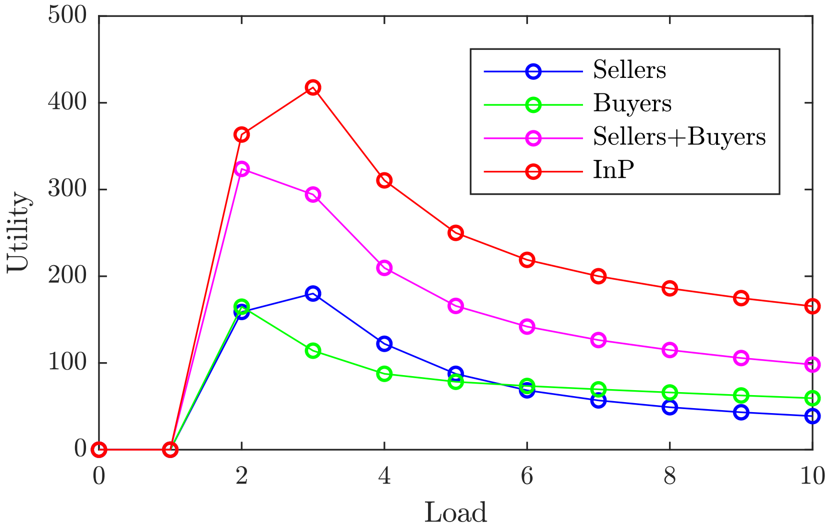
Figure 4.7 shows the utility distribution between the trades and the InP. The utility of all the traders decline as the load saturates the network and the volume of offered capacity drops. Consequently, the total number of trades experiences reduction.

Social Welfare

Figure 4.8 provides an insight into the social welfare (aggregate market utility averaged over the simulation time) generated by auctioning the excess capacity of the PON. The unit for utility is one block (XGS-PON frame block), e.g., the utility of 1000 in the Figure 4.8a means that on average over 10 seconds of simulation time ≈ 1000 additional frame blocks worth of utility is gained when using the proposed mechanism. The results in Figure 4.8 provides further support for the hypothesis that the proposed mechanism achieves higher social welfare compared to that of the Xu et al. [101]. The explanation for this difference lays in our trade reduction technique that reduces fewer trades compared to the Xu et al. [101]. We recognize that the significant improvements in Figure 4.8a that reaches up to ≈ 40% may seem unrealistic at first glance. To explain this, it is important to note that as the network load increases, the number of eligible traders is reduced since it becomes less likely for a VNO to have any excess resources to share. Therefore, it is likely that the trade eliminated by the trade reduction algorithm might be the only efficient trade, i.e., the Xu et al. trade reduction technique might ban the only feasible trade thus leaving the market with no additional social



(a) Unbalanced



(b) Balanced

Figure 4.7: Utility Distribution in the Marketplace

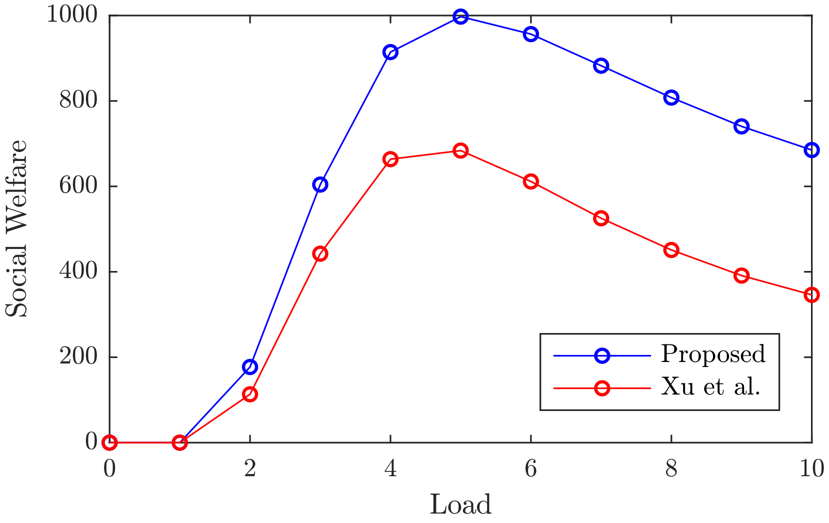
welfare.

4.6 Conclusions

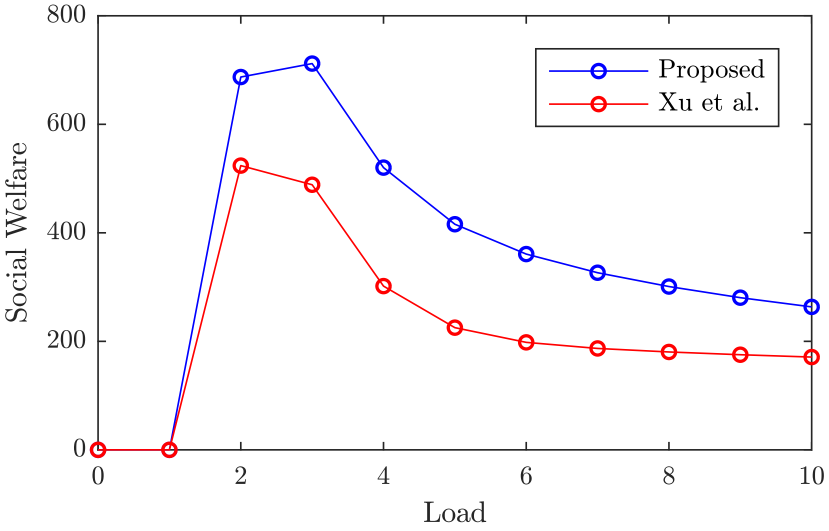
In this chapter, we addressed one of the economic challenges facing the realization of PON sharing. We provided an answer to the following research questions:

- *Could monetization of excess resources incentivize the operators to share their excess resources with competitors?*

  We designed a market model for PON excess capacity sharing, where multiple VNOs can engage in the trade of excess resources and receive monetary compensation for



(a) Unbalanced Load



(b) Balanced Load

Figure 4.8: Simulation results of our DBA auctions, showing how the auction mechanism increases the average Social Welfare.

sharing their resources with other VNOs. The following will benefit from the proposed marketplace:

- The VNOs will be able to monetize their idle resources and also provide higher peak information rate (PIR) for their customers while reducing the risk of over-provisioning.
- The InP can more efficiently utilize its infrastructure, allowing it to support more operators with no extra Capital Expenditure (CapEx).
- The end-users can enjoy more realistic information rates offered by the operators and reach a better quality of experience (QoE).

- *Could an economic robust double auction mechanism provide market participation in-*

centives for inter-operator network sharing?

We proposed a new sealed-bid, multi-item, double auction mechanism to efficiently allocate the resources while maximizing the social welfare of the market. The auction is designed to minimize any communication delay that could affect the PON scheduling operation, which typically occur every 125 μs. For this purpose, VNOs send all the required information for conducting the auction at once, along with the BMap. We have proven that our proposed algorithm is compatible with the VNOs' incentives and guarantees a positive budget for the InP. The results from the market simulation show that the proposed mechanism outperforms the state-of-the-art double auction mechanism proposed by Xu et al. [101], as our trade reduction mechanism scarifies fewer trades to achieve the crucial economic properties. Finally, these achievements are reached while the mechanism adds no additional communication overhead to the system due to its single-rounded nature.

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5 Blockchain-Based Distributed Sharing Market

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Blockchain-Based Distributed Sharing Market

> *"Concentration of executive power, unless it's very temporary and for specific circumstances, let's say fighting world war two, is an assault on democracy."*
>
> —Noam Chomsky

In chapter 4, we proposed a network sharing market mechanism to incentivize network tenants to trade their excess capacity with others in return for monetary compensation. However, the model in chapter 4, relies on a central market mediator, the Infrastructure Provider (InP), who is in charge of conducting the market and record-keeping. In this chapter, we identify the problems associated with such a centralized market. In section 5.1, we propose a distributed resource sharing market model to address the challenges of relying on a central entity. In section 5.2, we introduce an evaluation methodology for blockchain Key Performance Indicators (KPIs) using which we study the application of the proposed distributed market model in two use cases. The first use case discussed in section 5.3, is the inter-operator Passive Optical Network (PON) capacity sharing and the second use case is Fifth Generation (5G) network slice brokering in section 5.4.

5.1 Distributed Resource Sharing Market

The traditional roles of the InP and Virtual Network Operators (VNOs) are being challenged with new market players such as Over-the-Tops (OTTs) and vertical market services (e.g., automotive, e-health, etc.) which are considered to be the major revenue generation sources for the future 5G networks. These are typical scenarios where network investment and 5G deployment would be very costly or unattractive for legacy operators; instead, verticals expect significant advantage (i.e., there is a large private value for specific applications that require 5G type of connectivity).

Moving from conventional static sharing towards on-demand/on-the-fly dynamic multi-tenancy [127] requires a network sharing management architecture that enables capacity brokering. To understand the importance of automating bilateral market business processes, it is necessary to know how the current process works. A bilateral trade market is a business environment where multiple traders in both seller and buyer roles can exchange commodities (e.g., network resources). A typical bilateral market trade can involve:

- The manual negotiation of the terms of trade between the VNOs. This includes price setting, which, if happens manually, will not allow dynamic high-frequency trading of the resources.
- Different interpretations of the negotiated terms. In such a case, a third-party authority (e.g., regulator, InP, etc.) could be summoned to solve the dispute; however, this implies additional delays and costs for the VNOs.
- Lack of trust among the VNOs and absence of a trusted central authority holding the market by enforcing the terms.

These issues might lead to the VNOs having no incentive to participate in a dynamic resource trading market.

Many resource/infrastructure sharing problems in the communications sector are modeled as bilateral trade markets as these markets are capable of supporting multiple participants on both sides of the market. The majority relies on solutions based on game theory, in order to match supply and demand [110–114]. One of the most prominent solutions is the double auction, which focuses on allocating commodities (i.e., resources) to the participants with the highest demand. The end goal is typically to achieve the highest Social Welfare (i.e., maximizing the aggregate of all participants' utilities) in the market.

In chapter 4, we proposed a double auction mechanism originally designed to incentivize inter-operator resource sharing in multi-tenant PONs. The auction mechanism is capable of providing an allocation scheme for the resources while assuring trust among the participants (i.e., providing positive incentives to avoid manipulative market behavior). However, in our previous work, we made the assumption that this market model depends solely on a central third-party authority (the InP), which is trusted by all of the market participants. This central authority is thus in charge of both record-keeping of the market data and conducting the auction on behalf of all participants.

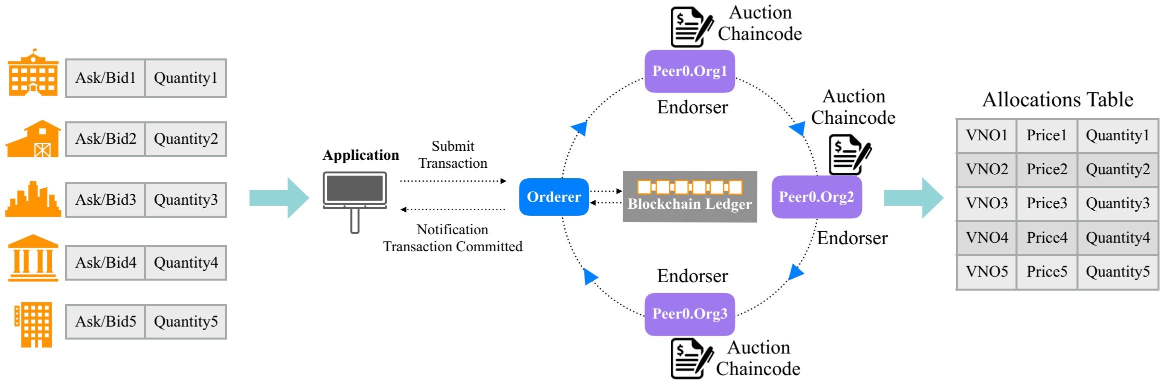


Figure 5.1: Distributed Market Model

Considering, however, that it is quite typical for an InP that shares its network to also offer services to customers, in competition with other VNOs, it is unrealistic to assume that VNOs will trust the InP. Being in competition with other VNOs, the InP could benefit from manipulating the market data or the process of the auction mechanism.

In this section we propose a new distributed model for bilateral trade markets, which eliminates the reliance on an impartial central authority. This is achieved making use of the two following features of blockchain technology (see section 2.5):

- Distributed record-keeping of all the transactions and participants' data using the distributed ledger technology.
- Conducting the auction in a distributed fashion rather than centralized, enabled by the smart contract technology.

A high-level view of the proposed distributed market model is illustrated in Figure 5.1. The application sends the transaction proposal to the orderer, to be broadcast to the peers in the channel. These peers are distributed across the VNOs' servers and are all part of the blockchain network. A **transaction** in the context of this market model is the process of receiving the bids/asks from the traders and conducting the double auction, matching eligible sellers and buyers, and issuing the results of the resource allocation. The peers proceed with the endorsement of the transactions (i.e., the auction) based on the predefined endorsement policy. The endorsed transaction is then returned to the application and sent to the orderer to finalize the ordering of the transactions into a block (using one of the consensus protocols available, e.g., Solo, Kafka, Raft).

Distributed markets have been previously studied in contexts such as advertisement marketplaces [128]. In [129], the authors propose a decentralized uniform-price double auction for the real-time energy market. Their solution is implemented using an Ethereum blockchain. They evaluate their model using metrics such as efficiency and the overall blockchain overhead cost.

5.2 Blockchain Performance Evaluation Methodology

A blockchain application operates over an underlying network of different components. The blockchain application handles the transactions submitted by the participating clients and proceeds to the verification and ordering process, throughout which, a block of transactions is generated and the transaction outcome is written on the distributed ledger. In the context of Hyperledger Fabric blockchain framework (see section 2.5), the performance of the blockchain application is closely tied to the performance of each component (e.g., peers, orderers, Certificate Authoritys (CAs), etc.) and the network that interconnects them. The performance of a blockchain application/network can be measured using the following metrics:

- *Transaction Throughput*, measured in Transactions per Second (TPS): The number of transactions that are processed by the blockchain and written on the ledger in a given second.

$$Transaction\,Throughput = \frac{Total\,Transactions}{Total\,time\,in\,seconds} \tag{5.1}$$

- *Transaction Latency:* The amount of time taken from the moment when a transaction is submitted until the moment when it is confirmed and is available on the blockchain. This includes the propagation time and the processing time due to the consensus/ordering mechanism.

$$Transaction\,Latency = t_{Confirmation} - t_{Submission} \tag{5.2}$$

- *Computing Intensity:* The amount of computing resources consumed by the blockchain operation throughout the operating time, including the processing power, memory, storage, I/O, and network. This metric is of great importance as it could determine the cost efficiency of a blockchain application. Furthermore, besides the capital expenditure for providing the computing capacity, blockchain networks could require huge amounts of energy to operate. Therefore, the computing intensity would also affect the operating

Table 5.1: Performance of Blockchain Frameworks

Platform/Metric	Bitcoin	Ethereum	Fabric
Average Latency	$\approx 10\, Min$	$\approx 12.5\, Sec$	$\approx MilliSec$
Throughput (TPS)	7	10 - 30	20,000 [130]

costs of the blockchain.

The performance of three major blockchain frameworks is compared in Table. 5.1. A more in-depth study of the performance metrics and evaluation methods is presented by the Hyperledger Performance and Scale Working Group [131, 132].

5.2.1 Benchmark Apparatus

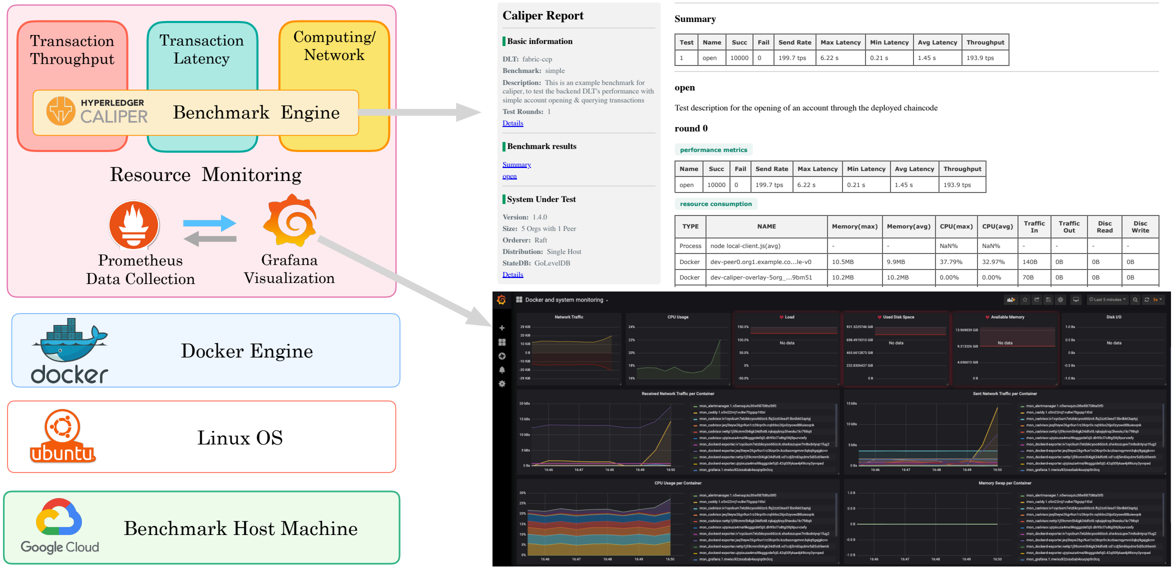
In this section, we briefly introduce the tools used for benchmarking the proposed blockchain application. The benchmark tool stack is depicted in Figure 5.2 where each benchmarking experiment produces two sets of results associated with the resource usage and blockchain performance. First, the report generated by Hyperledger Caliper (Shown in the top right corner of Figure 5.2) regarding the blockchain network performance indicators introduced in section 5.2. Second, a container-specific visual resource monitoring report generated by Grafana (bottom right corner of Figure 5.2) reflecting the network and system-level resource consumption. We also provide an insight into the cloud-based deployment environment and implementation details.

Hyperledger Caliper

Hyperledger Caliper [133] is one of the sub-projects under the Linux Foundation's blockchain initiative, which is designed to provide a benchmarking and performance evaluation tool for various blockchain frameworks (e.g., Sawtooth, Fabric, Etherium and more). In this dissertation, we use Hyperledger Caliper to evaluate the performance of our proposed distributed sharing market.

Data Collection: Prometheus Monitor

Prometheus [134] is an open-source monitoring and alerting toolkit that collects real-time metrics from the running jobs on the nodes spread over the network (i.e., the Docker overlay



Caliper Report

Basic information

DLT: fabric-ccp
Benchmark: simple
Description: This is an example benchmark for caliper, to test the backend DLT's performance with simple account opening & querying transactions
Test Rounds: 1
Details

Benchmark results

Summary
open

System Under Test

Version: 1.4.0
Size: 5 Orgs with 1 Peer
Orderer: Raft
Distribution: Single Host
StateDB: GoLevelDB
Details

Summary

Test	Name	Succ	Fail	Send Rate	Max Latency	Min Latency	Avg Latency	Throughput
1	open	10000	0	199.7 tps	6.22 s	0.21 s	1.45 s	193.9 tps

open

Test description for the opening of an account through the deployed chaincode

round 0

performance metrics

Name	Succ	Fail	Send Rate	Max Latency	Min Latency	Avg Latency	Throughput
open	10000	0	199.7 tps	6.22 s	0.21 s	1.45 s	193.9 tps

resource consumption

TYPE	NAME	Memory(max)	Memory(avg)	CPU(max)	CPU(avg)	Traffic In	Traffic Out	Disc Read	Disc Write
Process	node local-client.js(avg)	-	-	NaN%	NaN%	-	-	-	-
Docker	dev-peer0.org1.example.co...le-v0	10.5MB	9.9MB	37.79%	32.97%	140B	0B	0B	0B
Docker	dev-caliper-overlay-5org_...9bm51	10.2MB	10.2MB	0.00%	0.00%	70B	0B	0B	0B

Figure 5.2: Blockchain Benchmark Tool Stack

network) and reports the results back to the central host. The collected metrics are kept as a time-series database, which could be accessed through the flexible query language provided by Prometheus.

Data Visualization: Grafana

Grafana [135] is an open-source interactive visualization tool written in Go Lang, which provides a wide range of options for visualizing data from different sources such as Prometheus. We use Grafana to visualize the collected data from Prometheus regarding the resource usage of the blockchain network containers.

Pragmatic Experimental Blockchain Deployment

An enterprise blockchain application enables several business partners to make collaborative decisions using smart contracts and keep secure logs of the transaction on a distributed ledger. This is done through the partner organizations contributing infrastructure to form the blockchain network. Since the main aim of blockchain is to decentralize the process of decision making and record-keeping, the most likely network deployment scenario is a distributed cloud environment. In other words, the participating organizations will dedicate a particular amount of resources to host the blockchain application components, including the peers, orderers, and CAs. However, in the academic literature, the distributed nature of blockchain networks is often overlooked. The majority of studies related to the applications of blockchain technology in communications carry out experiments with limited resources, where the entire blockchain network (and the components) is hosted in a single machine or often on multiple Virtual Machines (VMs) in a server. This implementation, however, is far from a realistic production scenario as it will not feature parameters such as the network propagation, which could become a bottleneck for highly frequent transactions carried out on the blockchain.

In this dissertation, we aim to take a step beyond merely developing proof-of-concept blockchain solutions and instead focus on pragmatic experiment design and deployment that reflects the realistic capabilities of the proposed blockchain-based solutions. Therefore we have exploited a range of enterprise-grade software solutions and cloud infrastructure to design the experiments that are briefly introduced in the remainder of this section.

Cloud Infrastructure The leading cloud providers are competing to gain a bigger share of the future cloud market for blockchain applications, with a handful of them already offering Blockchain as a Service (BaaS) and being actively involved in the open-source blockchain communities [136]. We deploy our blockchain solution using multiple VMs on the Google Cloud Computing Engine, where we secured an academic research grant (credits) to conduct our research. These VMs are collocated at the same geographical region/zone (us-central1-a). The experiments are conducted by isolating one VM for the monitoring and benchmarking purposes and the other VMs hosting the participating organizations' blockchain components.

Container Orchestration: Docker Swarm Hyperledger Fabric utilizes Docker containers to host the blockchain components. Therefore, a blockchain application implemented using Hyperledger Fabric is often comprised of several containers per organization. This makes manual initiation and the management of the containers very difficult. To automate this process, we use docker-compose scripts along with the Docker Swarm technology to orchestrate the containers during the experiments. This allows us to seamlessly create numerous containers using pre-defined images and deploy them across the Swarm overlay network.

Strengths and Limitations Throughout the research leading to this dissertation, we have made every effort to use open-source and publicly available software to conduct the experiments. This will facilitate reproduction and further research based upon our work. Furthermore, we have used the material gathered through the literature review of this dissertation to organize tutorial talks at international conferences to disseminate our knowledge about the blockchain field. Meanwhile, we have communicated our expertise with the open-source community such as Linux Foundation's Hyperledger Telecom Special Interest Group [137] where we received feedback about our research from a wide range of industry and academic participants.

As for the limitations of the experimental research methodology, a blockchain application's performance depends on a range of tunable parameters. These parameters include block size, the choice of state database (e.g., GoLevelDB vs. CouchDB), the geographical distribution of the blockchain peers, the endorsement policy, and the consensus protocol. Each one of these parameters could significantly impact the performance indicators of the blockchain network. For instance, a bigger block size could increase transaction throughput while increasing the latency. Therefore, considering the vast number of design choices and implementation options in one hand and the limited available experimental infrastructure and time, we had to content ourselves with the most significant design choices and leave the remainder for future work.

5.3 Distributed Verification Model for PON Sharing Market

Conventional telecommunications infrastructure ownership models are being challenged as new market players are rising through the 5G evolution. This evolution involves the need for higher capacity and, therefore, higher network infrastructure investment and, in particular, the access network which provides the last-mile connectivity to the end-users [48]. In the fixed access network domain, PONs are at the core of this ownership evolution, as PON sharing (across services and tenants) is a main enabler of high-density, high-capacity data-transport in 5G networks [118]. PONs are fiber-optical telecommunications access network solutions that owe their popularity to high split ratios, and the passive nature of their optical distribution network which does not require any active component and their wide coverage (typically 20 kilometers, but up to 90 km in Long-reach PON [7]). PONs are one of the most widely deployed access solutions that traditionally provide broadband access using Fiber-to-the-Home (FTTH) and Fiber-to-the-Curb (FTTC) architectures.

The ideal situation for network sharing is an open-access model, where multiple competing VNOs share a network owned by an independent third party (left-hand side of Figure 5.3).

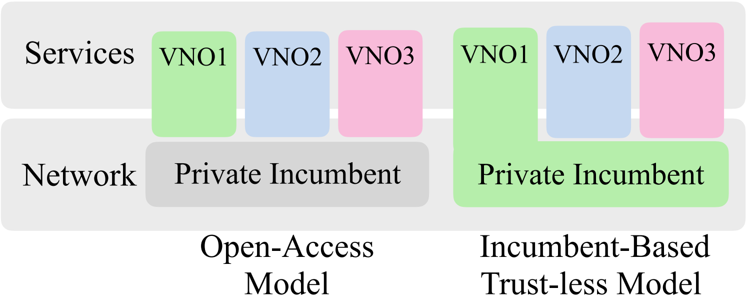


Figure 5.3: Access Infrastructure Sharing Models

In a highly-dynamic resource-sharing scenario, VNOs and InPs need to exchange network capacity using automatic auctioning mechanisms. As previously demonstrated in chapter 4, the InP can act as an auctioneer while the VNOs can buy/sell capacity on-demand to maintain the capacity and latency performance required for some of their services. These conventional ownership models would rely on a central trusted authority (the InP) to invest in deployment, oversee, and regulate the operations and provide revenue assurance. Today, however, often the InP is a private entity (typically the incumbent operator) that is also an operator, using the same shared infrastructure to serve its own customers (shown in the right-hand side of Figure 5.3). In this more typical incumbent-based model, since the InP is both auctioneer and VNO (thus it is not an independent third party), the other VNOs cannot trust it to operate the market (i.e., the resource redistribution mechanism).

On the other hand, the highly heterogeneous nature of the services and applications that 5G and beyond networks are expected to support, suggests that telecoms markets will become more diversified, with new players joining. For example, we are already experiencing an increase in the number of private operators that can offer dedicated services to industry (Industrie 4.0 being the main framework for such scenarios). Especially where public networks are required (e.g., in under-served rural areas with low population density), network sharing, across services and tenants, becomes a major enabler for increasing capacity while keeping the total cost of network ownership under control [138]. However, as mentioned above, a centralized model is unlikely to suit such an increase in diversity, and new market models are thus required to support this evolution. One of the key points of this new market structure is the replacement of the centralized market control with a distributed system that does not rely on any single third-party to provide a trusted environment.

The use cases of such distributed resource sharing markets are manifold, spanning from

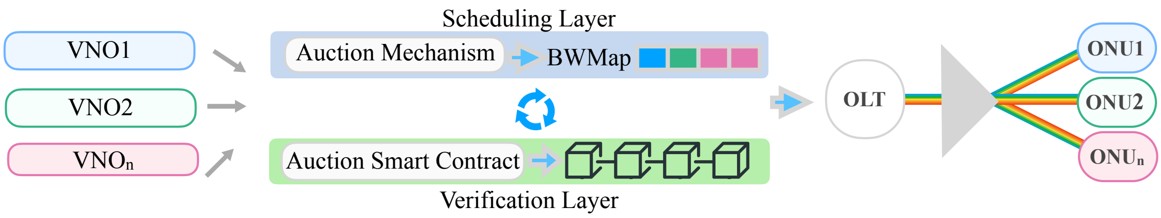


Figure 5.4: The Blockchain-Enhanced PON Sharing Model

sharing wireless spectrum [139] to data center cloud resources [140]. In this section, we focus on PONs, which operators are increasingly considering as a suitable option for supporting the high densification scenarios envisaged by 5G and beyond networks [8]. Precisely, we address the dynamic auctioning of PON excess capacity to incentivize network sharing across competing VNOs operating over the same physical infrastructure.

Our approach is thus to enhance the market mechanism proposed in chapter 4 with a parallel verification mechanism using a blockchain implementation on the Hyperledger Fabric blockchain framework [115]. This enables all players to verify the previous transactions at any time, through sending queries to the state databases that are synchronized with the distributed ledger. This provides full transparency on the capacity allocation mechanisms, which makes the auction workable also in the absence of a trusted third party.

Blockchain technology offers the following advantages:

1. Reliable and robust transaction flow provided by blockchain consensus mechanisms such as RAFT [116].
2. Transparent transactions and record-keeping enabled by the distributed ledger technology.
3. Immutable transaction logic enabled by the smart contract technology where a single party cannot unilaterally alter the terms of the contract.

Figure 5.4 shows the proposed blockchain-based verification model enhancing trust in Dynamic Bandwidth Allocation (DBA) auctions. In this model, the InP conducts the auctions that enable VNOs to exchange excess capacity among each other. Since we aim to apply this approach also to low-latency 5G and beyond services, we decouple the DBA auctioning mechanism (which occurs every PON frame, as demonstrated in chapter 4) from the blockchain-based verification step. The upstream scheduling of the PON (i.e., the scheduling layer in Figure 5.4) will thus continue uninterruptedly while the verification layer assures correct conduct of the auction using distributed Smart Contracts.

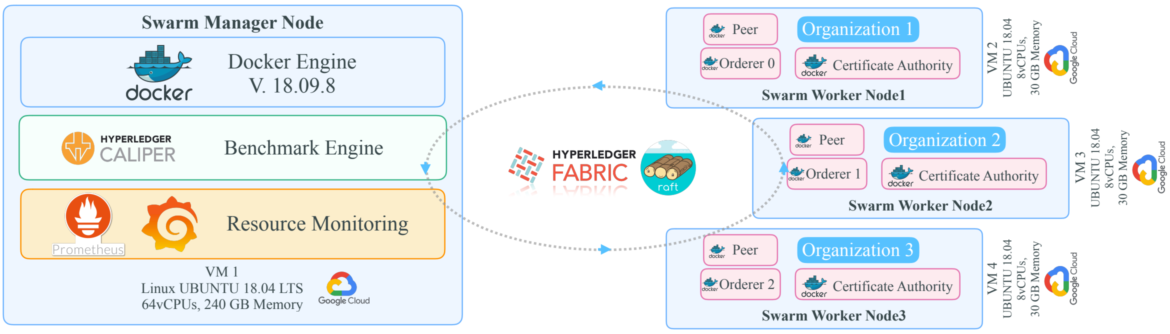


Figure 5.5: The Experiment Setup for PON Market Verification

The Scheduling Layer

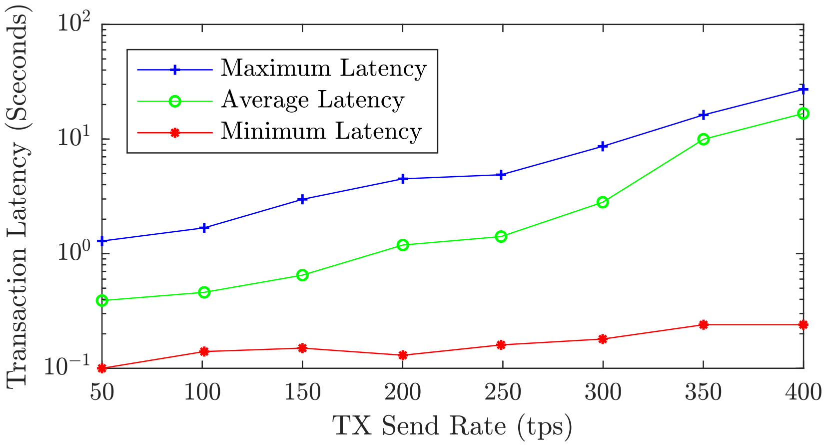
The scheduling of the PON upstream transmission opportunities is executed in the scheduling layer. Following the virtual DBA (vDBA) architecture, introduced in chapter 3, the VNOs send their capacity availability/demand for the next upstream frame to the scheduling layer, where the auction mechanism [114] matches the highest bidders with the cheapest sellers to release the final Bandwidth Map (BMap). The auction mechanism assures economic robustness in the resource allocation process or, in other words, guarantees that no participant could manipulate the market to their own benefit. This BMap then is broadcasted to the Optical Network Units (ONUs) to grant them slots in the next upstream frame.

The Verification Layer

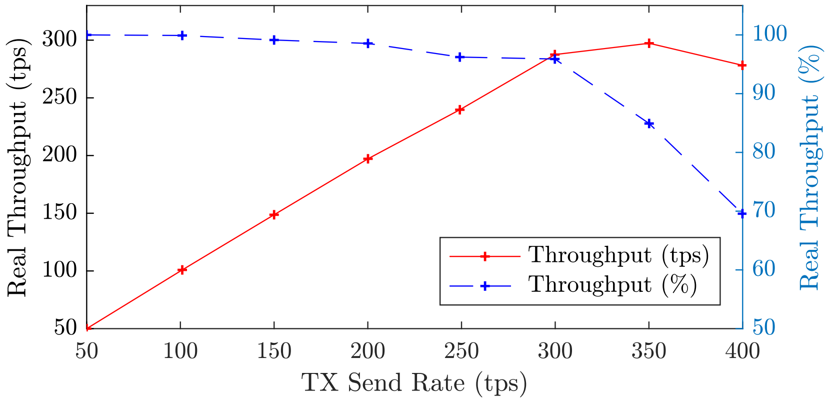
The proposed distributed verification layer is hosted in VNOs' servers and validates every single transaction (including the auction). At the same time, an append-only copy of the records is kept on a ledger hosted on VNOs' servers. This is possible thanks to the Smart Contract technology, which enables automatic enforcement of certain pre-negotiated terms of business among stakeholders of an enterprise ecosystem. We use a private/permissioned blockchain to deploy the verification layer. Contrary to public blockchains (e.g., Bitcoin), private blockchains support high transaction throughput and considerably lower latency.

5.3.1 Experiments and Results

To develop the verification layer functionality, we have used Hyperledger Fabric version 1.4.1 with Raft consensus, and Transport Layer Security (TLS) enabled. The system under test



(a) Send Rate V. Latency



(b) Send Rate V. Transaction Throughput

Figure 5.6: Benchmark Results: Send Rate V. Latency and Transaction Throughput

(Figure 5.5) includes four VM instances hosted by Google Cloud computing engine. We emphasize that this distributed cloud-based implementation, where each market player (i.e., the VNOs and the InP) operates its own independent VM, makes our system implementation highly realistic, as transactions are transmitted across different VMs, owned by the different players, and enables us to test its performance on a real cloud environment. Since the blockchain network components are deployed as Docker containers in Hyperledger Fabric, we use Docker Swarm to orchestrate the containers and manage the overlay network that connects the cloud nodes. VM1 (64 Virtual Central Processing Units (vCPUs), 240 GB Memory) is the Docker Swarm manager and is hosting the Hyperledger Caliper benchmarking tool (and the workload generator). VMs 2, 3 and 4 (8 vCPUs, 30 GB Memory) each hosts one organization (i.e., a VNO and/or InP and their related components). In total, we simulate 10 different bidders, as each VNO can bid on behalf of multiple different services. The Fabric network containers are orchestrated using Docker Swarm and clustered based on the organization to which they belong.

We run the experiments for 20,000 auction transactions with gradually increasing send rates from 50 to 400 TPS. Figure 5.6 illustrates the benchmark results of the auction application deployed on the Hyperledger Fabric network. The maximum, average, and minimum transaction latency under different send rates are shown in Figure 5.6a. As the transactions are sent to the network with a higher rate, the latency increases considerably. The system under test has been set up with adequate resources to minimize the computing power dependency of the results. Thus the radical increase in average latency for scenarios with more than 300 transactions per second means we are reaching the current scalability performance of the Hyperledger Fabric framework.

In this section, we proposed a distributed market mechanism for PON sharing where reliance on a central intermediary is mitigated and replaced by a blockchain-based smart contract. The smart contract assures reliable conduct of the market by holding the VNOs accountable through verifying the outcome of the auction mechanism using an endorsement policy. In conclusion, our current result of achieving 300 transactions per second, before the performance drop (shown in Figure 5.6b), provides the ability to verify upstream capacity blocks, each aggregating 25 upstream frames (i.e., every 3 milliseconds), demonstrating the ability to prevent and promptly detect market manipulations. In parallel, improving the throughput capacity of Hyperledger Fabric is also being pursued by researchers [130]. In the future, we plan to make use of the smart contract technology to enhance the mechanism introduced in this section with automatically enforceable quality assurance and Service Level Agreement (SLA) management.

5.4 Distributed 5G Network Slicing Marketplace

What differentiates 5G from its predecessor generations of cellular communications is that it goes beyond merely multiplying the network capacity and speed and promises an ambitious vision where various services with vastly different functional requirements are seamlessly hosted over the same physical infrastructure without affecting each others' performance [141]. This vision, in addition to many technical and standardization challenges that need to be addressed, demands a new approach to business and ownership models of network infrastructure [48], where automated resource orchestration and provisioning mechanisms handle on-demand resource needs of the operators. The most prominent model of resource allocation for 5G networks is slicing, which allows building customized logical networks on top of a shared physical infrastructure [142]. Thanks to the virtualization technologies, it is now possible to allocate virtual instances of the physical infrastructure while assuring seamless functionality using slice isolation techniques. As envisioned by 3rd Generation Partnership Project (3GPP) [143] in a highly heterogeneous network sharing ecosystem, network slices could be created to accommodate different functional and performance requirements of the network operators. This vision could see the emergence of a new market where a wide range of network operators, infrastructure providers, or public authorities carry out highly frequent transactions involving the exchange of resources, financial commitments, and post-deal operations. In other words, the conventional manual processing of these transactions is not feasible; therefore, novel automated process management methods have to replace them. The new automated process management has to enable flexible resource provisioning for key players of this market and accommodate their quantitative and qualitative expectations from the network resources dedicated to them.

Typical business processes in the communications industry include economic models (e.g., auctions) that aim to solve resource management problems using pricing and allocation mechanisms [144]. The main objective of these mechanisms, including the slice brokering [110] is to efficiently allocate the available resources to the parties with the most critical demand while assuring the manipulation-proofness of the scheme. Nonetheless, the common assumption in these studies is the existence of an impartial central authority who could be trusted to conduct the market operations and execute the business processes without manipulating the outcome to its or another party's benefit. We will challenge this assumption throughout this section and will illustrate how blockchain technology, along with smart contracts, could provide a distributed alternative to the conventional centralized approach to slice brokering. Blockchain technology has already proven to provide solutions for similar problems in various trust-less industrial ecosystems such as healthcare [145], manufacturing [146], and banking [147].

To the best of our knowledge, this section presents the first pragmatic implementation of a blockchain application for network slice brokering where the blockchain network is distributed on a commercial cloud environment and depicts realistic network/system-level KPIs such as latency, throughput, and computing resources. These realistic performance indicators are critical for providing a practical feasibility analysis of the proposed distributed slice brokering market.

Network slicing provides a solution to the diverse infrastructure/resource requirements of modern telecommunication networks. This is done through generating on-demand virtual instances of an end-to-end network on a physical infrastructure [148]. This enables service providers to serve their end-users with the utmost flexibility.

In [127], the authors have reviewed the business requirements and standards in the context of multi-tenant mobile networks. They have introduced in detail the architecture of the 5G network slice broker. The idea of the on-demand capacity broker is to enable allocating a portion of the network capacity for a specific time slot to a secondary resource user (Mobile Virtual Network Operator (MVNO) or OTT provider). They define a network slice as:

> "A network slice refers to an isolated amount of network capacity customized to best suit specific service requirements [127]."

In other words, a network slice is considered a complex commodity comprised of various resources required for providing services over a network. This commodity (network slice) is traded in a market in the form of leasing (temporary ownership) for a particular time-slot with pre-negotiated quantitative measures. The key factors in defining a network slice are:

- The composition of the slice (quantitative description of the slice components, e.g., Radio Access Network (RAN), computing, and storage)
- The time duration of the leasing
- The metrics that determine the expected performance of the slice (e.g., availability, Quality of Service (QoS) usually in the form of a SLA)

Considering the above definition, a network slice can be treated as a commodity with a typical supply-chain which has to be sourced from multiple suppliers (the InPs or other MVNOs who are willing to share parts of their idle resources) and be delivered to an intermediary business customer who then would serve its end-users using this network slice. Therefore the first function of the network slicing supply chain is the sourcing of the slice, i.e., acquiring the required resources for creating a slice with a particular configuration. From the slice requester's perspective, the aim is to acquire the slice with the necessary configuration for the lowest price from the market. On the other hand, from the suppliers' (the InP or MVNOs with excess resources) point of view, the optimal outcome is for the slice to be sold for the highest possible price. Game theory has been widely used for similar markets in communications research where multiple players are involved on both sides of the market [149]. Auctions, in particular, are very popular as market resolution tools [144]. The resources that are traded in these resource markets range from spatial streams [93] to spectrum/antennas [150], and resource blocks [151].

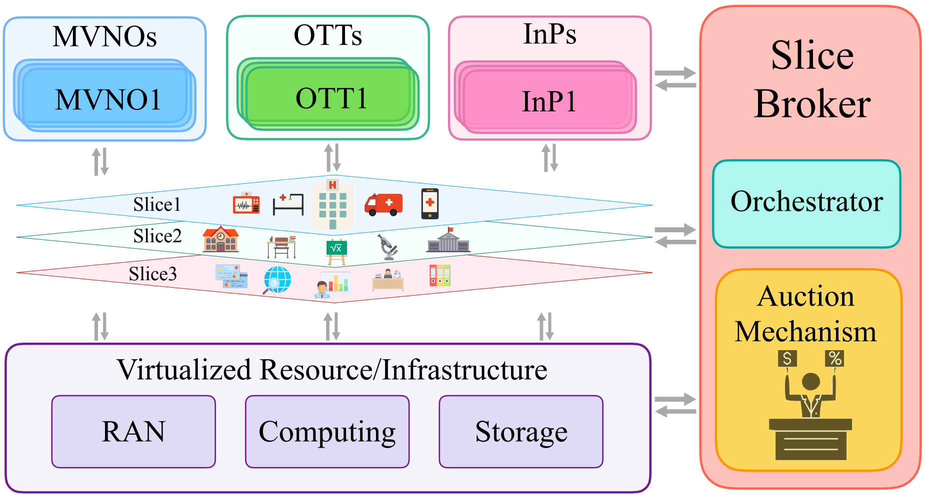


Figure 5.7: The Slice Broker Model

Among these game-theoretical solutions, we are more specifically interested in auction mechanisms that are capable of handling multiple traders in both the selling and buying sides of the market. Such two-sided auctions are referred to as double auctions in the literature. A slice broker equipped with a double auction would allow service providers, network operators and infrastructure owners to participate in a market capable of creating on-demand network slices (depicted in Figure 5.7). A vertical market for network slices will provide new network infrastructure monetization opportunities by welcoming new market players (e.g., automotive industry, e-health, etc.) and increasing the infrastructure utilization through multiplexing gains provided by more slice requests [152]. Double auctions will further enhance the slice brokering operation by allowing the operators to monetize their underutilized resources.

Multiple placement options for the slice broker have been proposed in the literature (e.g., in the SDN controller [153] or the orchestrator [127]). However, what is common with most of these proposals is that the brokering mechanism is hosted by a single entity that is not necessarily impartial and might have incentives to manipulate the outcomes of the mechanism. In this section, we propose a distributed slice brokering model which allows two-sided trade of the resources required to create a slice of the network. The traded commodity in this market is either a unit-bundle of different resource types (RAN, computing, or storage) or a single type multiple-unit of each resource type. The distributed brokering model is based on smart contract technology and mitigates the reliance on a central authority to operate the slice broker.

The application of blockchain technology for slice brokering have been previously studied in the literature. In [154], the authors present a feasibility analysis of a network slice broker using blockchain that enables dynamic slice acquisition for automated industrial processes. Their results show that the analyzed industrial micro-processes can benefit from adopting a blockchain-based 5G network slice broker and the distributed ledger technology. However, the authors have not endeavored to implement the use case on the blockchain and have settled for theoretical analysis. The authors in [155] have proposed a blockchain-based network slice broker for 5G services to secure and ensure anonymous transactions using blockchain. They have developed a proof of concept to evaluate the performance of their proposed slice broker. Their proposed blockchain platform is based on a consensus mechanism called Hashcash [156]. Their performance evaluation is, however, only limited to comparing the average time of sub-slice contract creation and slice deployment. They conclude that the additional security and privacy provided by blockchain does not have a significant impact on the performance of the slice broker. Hashcash is a public blockchain that uses a Proof of Work (PoW) based consensus protocol which relies on the network nodes solving computationally complex problems to reach consensus [157]. Although PoW consensus due to its pseudo-anonymous nature could be the most robust and secure option for particular applications (e.g., crypto-currencies), in enterprise ecosystems such as telecoms, they appear to be redundant as the parties involved in the blockchain are already known to each other. Therefore, permissioned blockchains that are designed for enterprise ecosystems and use more straightforward and less resource consuming consensus protocols such as Raft [116] are considered a better fit.

In this section, we use an implementation of the double auction mechanism introduced in chapter 4, which enables multiple traders in both sides (seller/buyer) of the market to trade their resources (multiple items simultaneously). The double auction mechanism assures manipulation-proofness of the market by decoupling the ask/bid value proposed by the traders from the final price paid; therefore, the traders cannot manipulate the market by strategizing over their proposed ask/bid value.

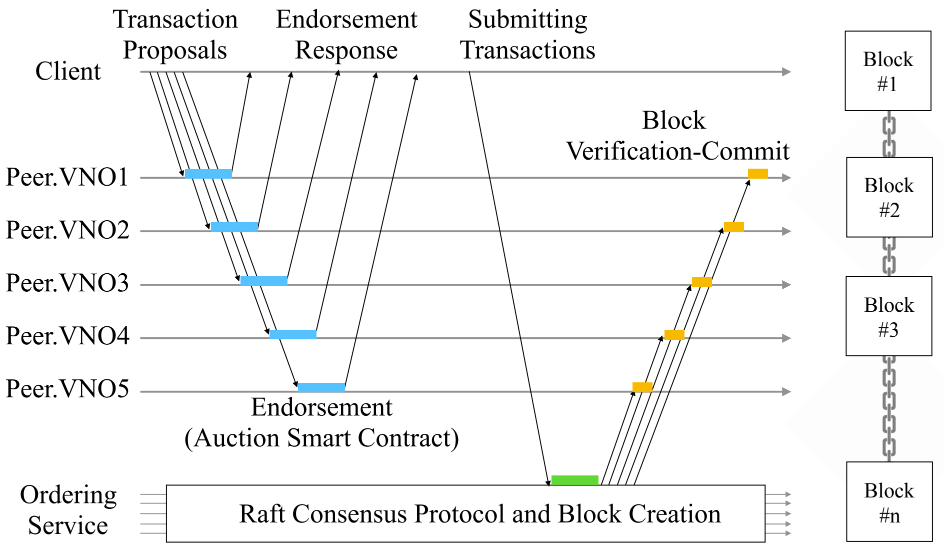


Figure 5.8: The Distributed Broker Transaction Flow

We define a unit of a network slice as $S = \{R, C, T\}$ where R, C, and T represent a single unit of RAN, computing, and storage, respectively. A buyer's request could be depicted as $R_i^b = q_i^b \times S$ where q_i^b is the quantity of slice units demanded by buyer i.

It is noteworthy that in the context of our slice brokering mechanism the traders can only trade multiple units of a pre-defined network slice. More advanced market mechanisms such as combinatorial auctions [158] could be used to allow more customizable combinations of resources between the operators. Other market mechanisms could be implemented in our proposed distributed brokering model by merely replacing the smart contract with a new algorithm.

We deploy the slice broker application on a realistic distributed implementation of Hyperledger Fabric to be able to evaluate the performance of the market with the reflection of real-world network latency and processing.

For example, in a cycle of the slice brokering process VNO1 which operates a network of Internet of Things (IoT) devices and is experiencing a temporary surge in data transmission submits a request (R_1^b) for a network slice to allow smooth transmission of data to/from the data center. Meanwhile, the InPs and other operators with idle resources announce their supply. Finally, the periodical auction smart contract is triggered in the blockchain application. The auction transaction flow in our proposed distributed slice brokering is depicted in Figure 5.8. First, the transaction proposals are sent to the blockchain peers. A transaction proposal consists of a table of ask/bid values, and the quantity of available/demanded

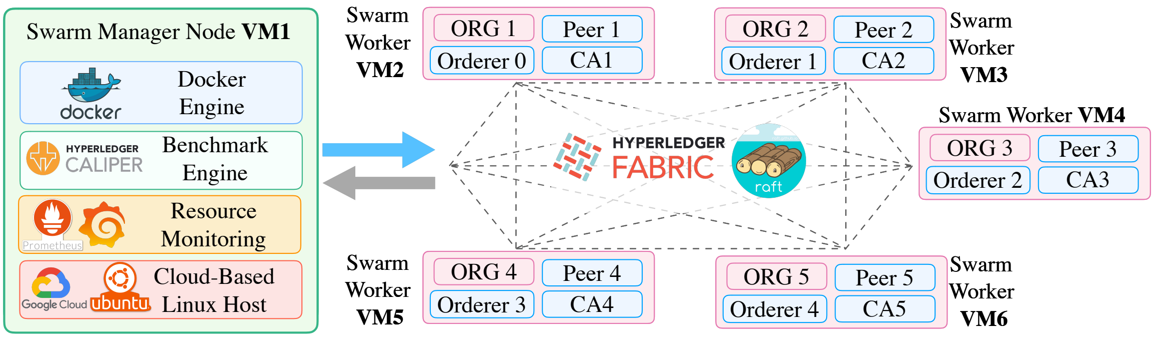


Figure 5.9: The Experimental Setup: Blockchain Network Architecture

resources proposed by each VNO along with the proposed (unverified) outcome of the double auction, which determines the identity of the winning traders and the quantity of trades. This process is initiated inside the client application and then broadcast to the peers of each blockchain member VNO. Once the peers receive the transactions, they begin the endorsement process by executing the chaincode, which contains an implementation of the brokering auction mechanism. If the resource allocation outcome resulting from the peer-run auction matches the proposed outcome, they endorse the transaction by returning a signed transaction. When enough number of endorsements is reached (this number depends on the endorsement policy that in our case is N-out-of-N, i.e., all the peers have to endorse), the transactions are sent to the ordering service, where the consensus is reached (i.e., Raft in our case). The final block is then created and committed to the ledger. Therefore, this distributed process replaces the conventional centralized approach to slice brokering, where a single authority does not control the entire conduct of the market.

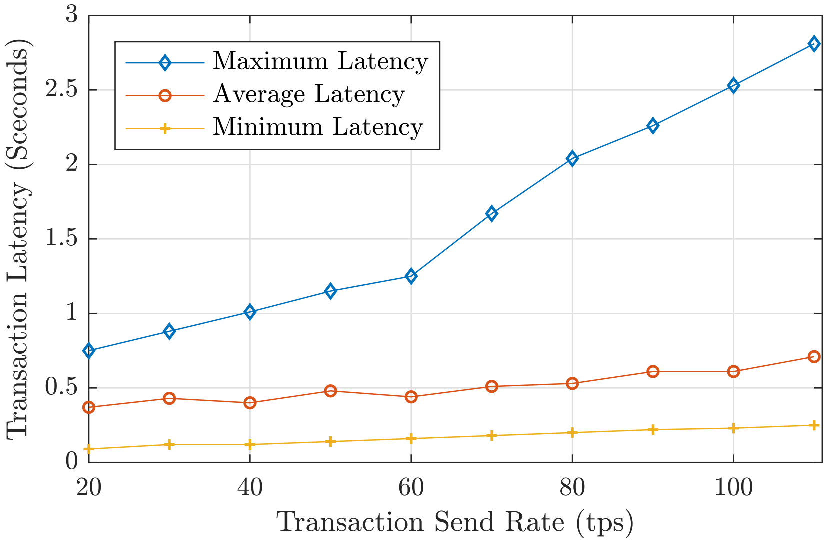
5.4.1 System Implementation and Results

We use the Hyperledger Fabric (version 1.4.1) framework to implement our blockchain application. To achieve realistic results, we deploy an under-laying network of nodes similar to a real-world production environment. The System Under Test (SUT) shown in Figure 5.9 consists of 6 VM instances. VM1 (8 vCPUs Intel(R) Xeon(R) @ 2.30GHz and 32 GB memory) hosts Hyperledger Caliper [133] which is a benchmark tool designed to measure the performance of multiple blockchain solutions. The blockchain network consists of 5 organizations, each hosting one instance of a peer, orderer, chaincode, and certificate authority (see section 2.5). These blockchain components are each deployed as a Docker container, and Docker Swarm is used to orchestrate the containers that are distributed across a network of VMs. VM1 is the Docker Swarm manager which is in charge of composing and deploying the containers at the beginning of the benchmark. VM2-VM6 (4 vCPUs and 15 GB memory) each host an organization and their containers. This provides a realistic implementation, where different organizations run their processing in different and independent virtual machines.

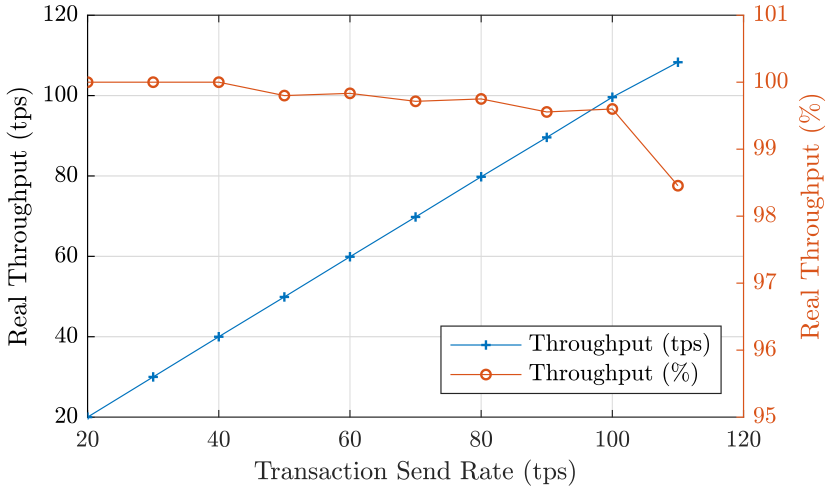
The experiment consists of multiple rounds of benchmarks with varying transaction send rates (from 20 to 110 TPS). For each benchmark, we generate 10,000 transactions (i.e., each transaction is one round of double auction) and submit them to the blockchain to measure the minimum, average and maximum transaction latency and transaction throughput. In addition, to evaluate the container-level computing and network resource utilization of the blockchain application, we use Prometheus [134], an open-source monitoring system, to record real-time metrics in a time-series database and then visualize these metrics using Grafana [135] visualization suite.

The minimum, average, and maximum transaction latency for each experiment is shown in Figure 5.10a. The minimum and average latency follow a semi-linear growth (with a different slope) as the send rate increases. The average latency remains below 1 second throughout the experiments. The maximum latency, on the other hand, grows more rapidly compared to the minimum and average latency and goes beyond 1 second as the send rate reaches 50 TPS. In real-time applications, the maximum latency is the bounding metric as it determines the feasibility of the application. The maximum latency, however, can be controlled using transaction processing timeouts, where necessary, and a default output for the transaction is defined. Figure 5.10b illustrates the transaction throughput of the blockchain application based on varying send rate. The throughput remains above 99.5% while the send rate is up to 100 TPS. However, a significant drop (down to 98.4%) in the throughput is experienced as the send rate is raised to 110 TPS, showing we have reached the highest usable rate.

Throughout each experiment, 20 docker containers are created and deployed on top of an overlay network to which all the VMs are connected. To get a better insight into the resource consumption and, therefore, the infrastructure footprint of the blockchain application, we have produced Figure 5.11, which depicts the container-specific CPU, memory and network utilization throughout one instance of the experiment. As previously mentioned, each component of the blockchain is implemented as a Docker container. For the purpose of clarity, CA containers are intentionally omitted from the visualization as their resource consumption



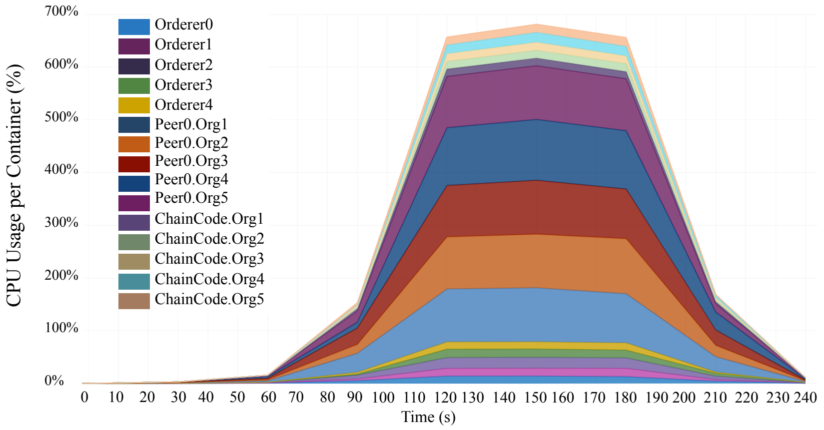
(a) Send Rate V. Latency



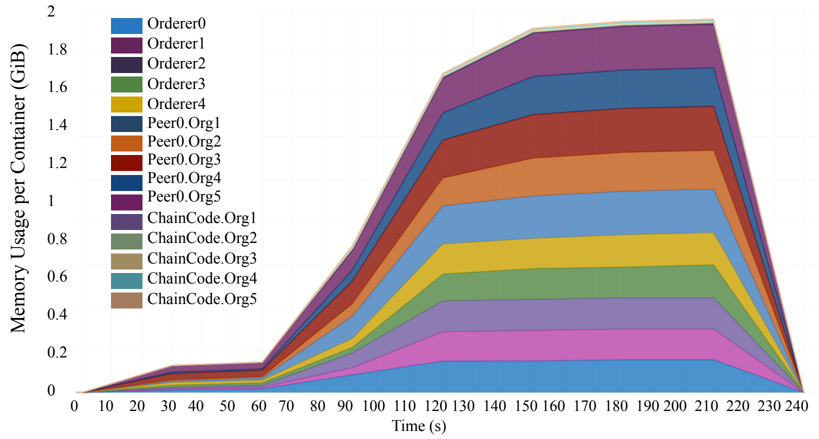
(b) Send Rate V. Transaction Throughput

Figure 5.10: Benchmark Results: Send Rate V. Latency and Transaction Throughput

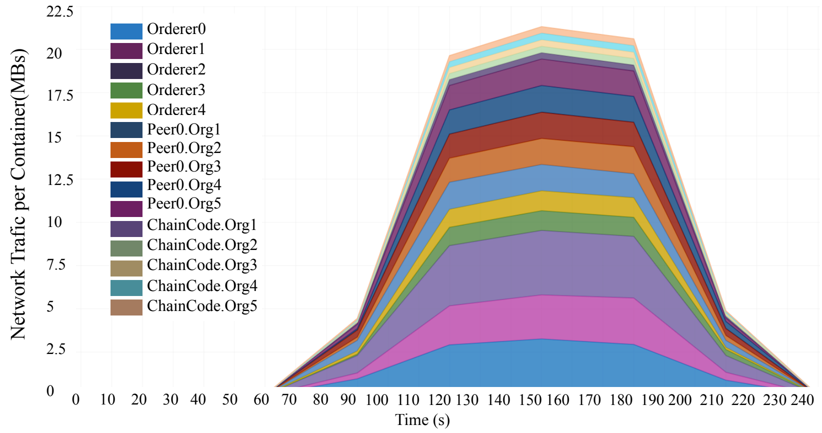
is negligible. Figure 5.11a depicts the CPU utilization of the containers. The peer nodes (tasked with the endorsement of the transactions) are using most CPU resources. This is due to the fact that the verification of the smart contracts (auction) outcome is done by the peers; hence, the high CPU usage. The memory consumption is illustrated in Figure 5.11b, where the peer nodes are consuming the most memory, followed by the orderers that also consume a considerable amount. Figure 5.11c shows the sum of incoming and outgoing network traffic to/from each container. As expected, the orderers occupy the biggest part of the network due to the highly-frequent signaling among the orderers to reach consensus. The results shown in Figure 5.11 could set guidelines for efficient resource management for blockchain-based slice brokering application. For instance, Hyperledger Fabric allows multiple peers per organization (e.g. where a degree of isolation is required between various departments). This would



(a) CPU Utilization



(b) Memory Utilization



(c) Network Utilization

Figure 5.11: Benchmark Results: Resource Utilization

entail higher demand for CPU. Further research could also be conducted to determine the infrastructure footprint of the slice brokering application under different architectural designs such as distribution of the orderers, and the number of peers per organization. Taken together, the results depicted in Figure 5.11 suggest that contrary to public blockchains such as bitcoin, Hyperledger Fabric enables us to implement the slice brokering blockchain application on standard cloud environments within a reasonable computing infrastructure footprint.

In this section, we proposed a distributed market design for 5G network slice brokering based on blockchain technology. We implemented a variant of the double auction mechanism as a smart contract to assure trust in a telcoms business ecosystem, where no trusted authority could control the resource sharing market mechanism. We have deployed a pragmatic network of blockchain nodes over six cloud-hosted VMs to achieve realistic performance measurements. Using the deployed blockchain application, which is powered by the Hyperledger Fabric framework, we conducted an analysis of the blockchain network performance in terms of latency and transaction throughput. These metrics are essential in designing blockchain-based markets as they determine the feasibility and frequency of resource trades over blockchain. Our experiments showed that our blockchain slicing market application is able to process up to 40 auction transactions per second while maintaining a 100% transaction throughput and an average latency of 500 milliseconds, with a maximum of 100 TPS, with throughout very close to 100 %. Meanwhile, as mentioned in [159], the time-scale envisioned for a 5G network slice provisioning and deployment is in the order of minutes. Therefore, our proposed market could support the simultaneous and real-time provisioning of multiple 5G slices without imposing any considerable latency to the process.

5.5 Conclusions

In this chapter, we proposed a distributed market model for inter-operator network sharing. The proposed market model addresses the lack of trust in a central authority to conduct the market, which poses a threat to the adoption of markets in emerging network ownership models. We introduced a distributed approach to the bilateral trade markets for future telecommunications networks. We first described the research areas where bilateral trade markets are being adopted and the game-theoretic solutions for the allocation of commodities. Then we argued that the current trust on the central third-party brokers might not be sustainable as new network ownership models will provide market manipulation incentives for these brokers. As the main contribution of this section, we illustrated how blockchain technology, along with smart contracts, can help the bilateral trade markets to function in an untrusted environment.

The proposed distributed market model provided an answer to the following research question:

Could the blockchain technology be leveraged to address the lack of trust in centralized network sharing markets?

We picked two use cases from the telecommunications industry, where centralized decision making poses a limitation. The first use case (section 5.3) is multi-tenant PON excess capacity sharing market described in chapter 4. We proposed a verification layer enabled by the proposed smart contract to conduct the auctions in parallel with the InP and therefore allow for auditing of the auction outcome as demanded by any of the parties. This is possible as the record of the market transaction is kept in the distributed ledger on the blockchain network.

The second use case is network slicing in 5G where the network operators, InPs, and OTTs could source the resources (RAN, computing, storage, etc.) required for their network slice from other parties using the provided market mechanism. The novelty of this use case is eliminating the dependency on a central broker to conduct the market and match the sellers and buyers.

To examine the feasibility of our proposals, we implemented the proposed market models using an open-source blockchain framework, Hyperledger Fabric. Finally, we reported the results of our experiments and analyzed how the proposed distributed markets perform under different loads and also how these differences affect performance metrics such as latency and transaction throughput. However, the performance of a blockchain system highly relies on the SUT and other properties of the blockchain such as block size, authorization methods, and consensus protocol. Therefore, further research is needed to asses the effect of these design choices on the 5G slicing market performance.

6 Summary and Open Challenges

> *"There are times when I feel like I'm in a big forest and don't know where I'm going. But then somehow I come to the top of a hill and can see everything more clearly. When that happens it's really exciting."*
>
> —Maryam Mirzakhani

The core objective of this thesis was to explore the potential of network sharing in the context of optical access networks, first, to assess the presence of motivations to adopt fine-grained active sharing. Second, to identify the technical and economic barriers that could prevent the stakeholders from embracing network sharing despite the intuitive motivations. And finally, to address these barriers using state-of-the-art technical and economic solutions. The high-level outline of this thesis is depicted in Figure 6.1.

6.1 Summary

In chapter 2, we provided an overview of the background as well a review of the state-of-the-art literature on the underlying concepts related to this dissertation. By doing so, we identified the motivations for optical access network sharing which included reducing total network expenditure and market barriers for new and smaller service providers, cultivating innovation and encouraging competition in the communications market. Therefore we answered the first part of the Research Question 1: *What are the motivations and implications for optical access network sharing?*. Regarding the second part of RQ1, three major implications arose, one technical and two economic. First, the technical implication of multi-service coexistence of network operators over the same physical infrastructure. Second, the lack of sharing incentives for competing operators and third, the emerging network ownership models that are expected

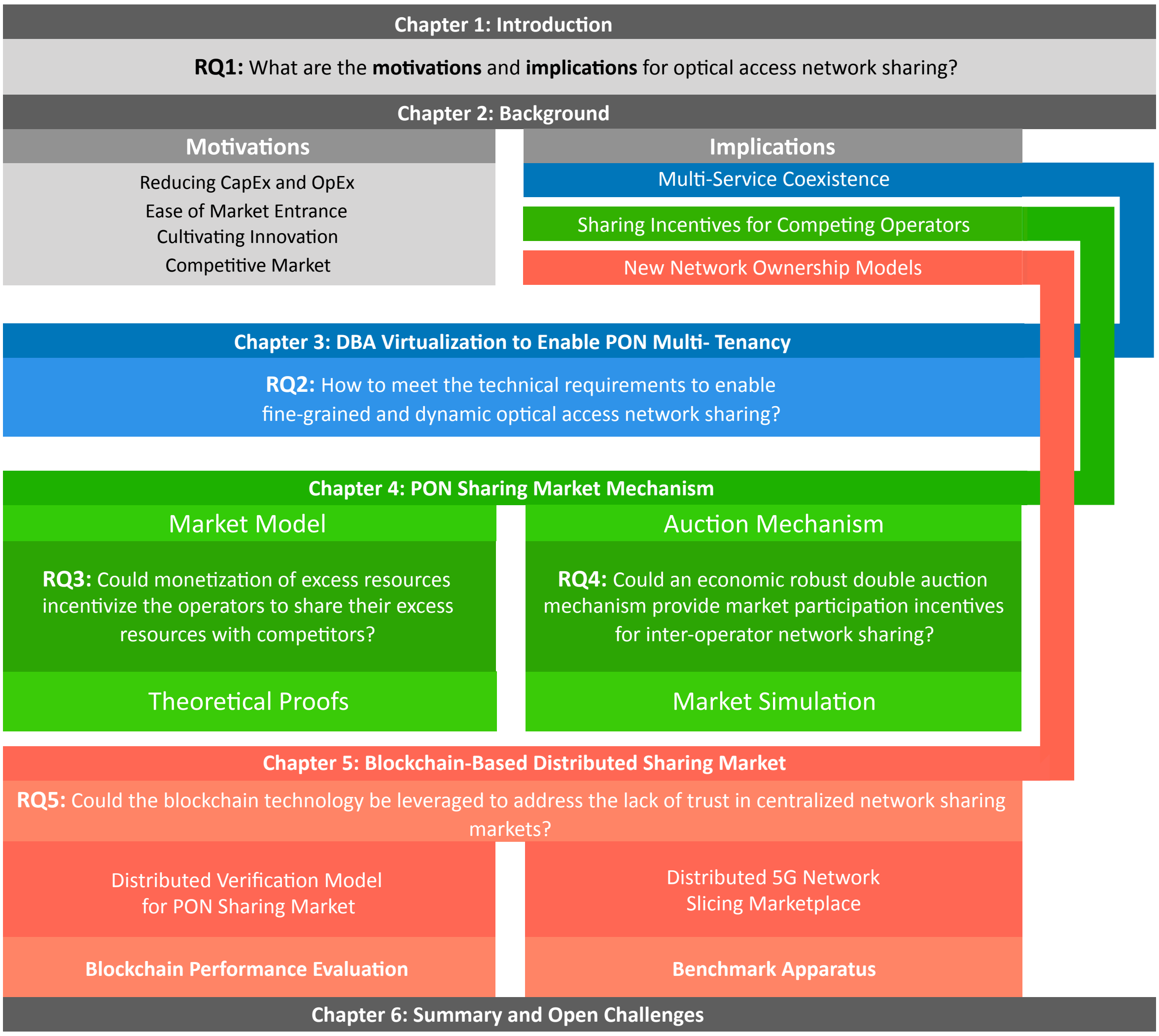


Figure 6.1: The Dissertation Outline

to disturb the balance of the conventional approaches in the communication networks' market. These implications then became the main theme of this thesis, producing RQ 2-5.

In chapter 3 we provided an answer to Research Question 2: *How to meet the technical requirements to enable fine-grained and dynamic optical access network sharing?*. We leveraged network virtualization technology to tackle the inflexible nature of the DBA algorithm that were not capable of supporting heterogeneous services due to the orthogonal performance requirements. We demonstrated how this inflexibility was a technical barrier to multi-service coexistence in PONs. We proposed the concept of vDBA that would allow the VNOs to operate their desired instance of upstream capacity scheduling thus meeting their service-specific QoS requirements. We finally described how the lack of economic sharing incentive for sharing the excess capacity among these operators motivated the RQ3.

In chapter 4 we addressed the Research Question 3 that was raised in the previous chapter.

RQ3: *Could monetization of excess resources incentivize the operators to share their excess resources with competitors?* We modeled the multi-tenant PON as a two-sided market where the VNOs with excess capacity can trade their resources with others in return for monetary compensation. We formally defined how the VNOs would valuate their excess capacity in such a market and how different strategies could affect their utilities in the market. Next, we acknowledged that in the absence of a manipulation-proof market mechanism the VNOs would use manipulative strategies to maximize their own profit without considering others' utilities. We argued that such a behavior would lead to distrust among the VNOs and eventually lack of trading activity. In response to Research Question 4: *Could an economic robust double auction mechanism provide market participation incentives for inter-operator network sharing?*, we propose a double auction mechanism that provides a matching between the seller and buyer VNOs. We used mathematical proofs and market simulation methodologies introduced in section 4.3 to assure the economic-robustness of the proposed auction mechanism. Furthermore, we compared the proposed mechanism with a state-of-the-art mechanism and the results showed up to $\approx 40\%$ improvement in terms of allocative efficiency (social welfare).

In chapter 5, we presented an alternative approach to the centralized conduct of the resource sharing market where no central entity is trusted by all the parties to manage the market. This new approach provides the answer to the Research Question 5: *Could the blockchain technology be leveraged to address the lack of trust in centralized network sharing markets?*, We used the blockchain technology to develop a distributed market-place that relies on a collaborative consensus rather than centralized control. The auction mechanism is implemented as a smart contract which requires all (or a subset) of the market players to endorse and verify the transactions occurring as the result of the auction. This smart contract once agreed upon is immutable the same way that all the transaction information recorded on the distributed ledger are immutable. Furthermore we acknowledged that replacing the centralized market management with a distributed approach will impose certain overheads to the system. To further explore, we used the blockchain evaluation methodology introduced in section 5.2 to study the feasibility of using the distributed market in two communication network scenarios. First, we proposed to enhance the multi-tenant PON market introduced in chapter 4 with a verification layer that is deployed on the blockchain and uses the distributed market mechanism to produce an auditable record of the PON auction transaction. Second, we addressed the 5G slice brokering problem. We replaced the centralized brokering of slices among different network operators with the blockchain-based distributed market mechanism. We designed pragmatic experiments to evaluate the performance of the distributed market mechanism under varying transaction send rates. The results of this study indicated that our proposed market mechanism can process up to 40 and 100 transactions per second with respectively no and negligible loss in transaction throughput. Meanwhile the average transaction latency under varying send rates remained under 1 second. These finding suggest that considering the slice brokering trade frequency that is expected to be conducted on a minute scale, our proposed distributed market could support the ecosystem without imposing significant overhead.

6.2 Open Issues and Future Work

In this thesis we made several contributions concerning the technical and economic challenges of optical access network sharing. In the following we provide a number of open challenges including extensions to the contributions of this thesis and potential research ideas inspired by the topics addressed in it for some of which future work is already underway by the author.

6.2.1 Comprehensive Blockchain Performance Evaluation Methodology

Provisioning the required resources for a blockchain-based distributed application depend tightly on one's ability to precisely evaluate the performance of a blockchain network. As mentioned in section 5.2 blockchain's performance can be affected by a number of parameters. These parameters include block size, the choice of key-values world state database (GoLevelDB vs. CouchDB), the geographical distribution of the blockchain peers, the endorsement policy, and the consensus protocol. However, we regarded the comprehensive investigation of these parameters outside the scope of this thesis. Therefore a future work can identify and elaborate on the performance metrics associated with blockchain applications and determine how these metrics affect the resource provisioning in terms of computing, network or memory costs. The outcome of this work could be a comprehensive methodology for feasibility and cost analysis of a blockchain application with a focus on application in the telecommunications area. This methodology would be of interest for a broad range of researchers and industries who are focusing on designing blockchain-based solutions.

6.2.2 Automatic SLA Enforcement using Smart Contracts

Service Level Agreements (SLAs) between network operators and infrastructure providers could play an integral role in network sharing. The SLA has to provide a detailed description of the expected reliability, availability and other performance metrics of the service and the actions to be taken in case of one of the parties breaching the agreement (i.e., the supplier not meeting the terms of the SLA). However, the enforcement of these SLAs remains an open challenge as manual enforcement and conflict resolution could become a bottleneck in the highly dynamic network sharing scenarios. Future work is already planned by the authors to first identify the SLA processes that could benefit from automation and second to investigate the possible implementation of this processes as smart contracts to facilitate automation. These smart contracts would trigger certain transactions based on the negotiated terms of agreement and keep a tamper-proof record of them on the blockchain ledger.

6.2.3 Distributed Data-Sharing Governance for Optical Networks

The autonomous operation of data-driven optical network management relies on the development of trusted interaction among all participants. For example, given the set of all available monitoring information, different parties should only have access to specific subset of the data, depending on their role (e.g., infrastructure provider, virtual operator, slice provider, end user, etc). Future work could investigate the issues associated with the governance of multilateral data-sharing in optical networks. A distributed market mechanism similar to the one proposed in chapter 5 could be used for data monetization using a credit-based system to incentivize sharing of the data. Furthermore, the access control mechanisms available in blockchain platforms could be leveraged for identity management and authorization in data governance.

Acronyms

List of Acronyms

3GPP	3rd Generation Partnership Project
5G	Fifth Generation
AE	Allocative Efficiency
BaaS	Blockchain as a Service
BB	Budget Balance
BBF	BroadBand Forum
BBU	Base Band Unit
BEREC	Body of European Regulators for Electronic Communications
BGP	Border Gateway Protocol
BMap	Bandwidth Map
BPM	Business Process Management
C-RAN	Cloud Radio Access Network
CA	Certificate Authority
CapEx	Capital Expenditure
CORD	Central Office Rearchitected as a Data Centre
CPE	Customer Premises Equipment
CPU	Central Processing Unit
DBA	Dynamic Bandwidth Allocation

DSL	Digital Subscriber Line
E-CORD	Enterprise CORD
EFM	Ethernet in the First Mile
EPON	Ethernet Passive Optical Network
ETSI	European Telecommunications Standards Institute
FANS	Fixed Access Network Sharing
FASA	Flexible Access System Architecture
FCC	Federal Communications Commission
FPGA	Field-Programmable Gate Array
FTTC	Fiber-to-the-Curb
FTTH	Fiber-to-the-HomeFiber to the x
FTTx	Fiber-to-the-x
G.Fast	Fast Access to Subscriber Terminals
GPON	Gigabit Passive Optical Network
IC	Incentive Compatibility
IEEE	Institute of Electrical and Electronics Engineers
InP	Infrastructure Provider
IoT	Internet of Things
IP	Internet Protocol
IQ	In-phase/Quadrature
IR	Individual Rationality
ITU	International Telecommunication Union
KPI	Key Performance Indicator

LAN	Local Area Network
LTE	Long Term Evolution
M-CORD	Mobile CORD
MAC	Medium Access Control
ME	Merging Engine
MSP	Membership Service Providers
MVNO	Mobile Virtual Network Operator
NFV	Network Function Virtualization
NG-PON2	Next-Generation Passive Optical Network 2
NTT	Nippon Telegraph and Telephone
ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONU	Optical Network Unit
OpEx	Operating Expenditure
OTT	Over-the-Top
P2MP	Ethernet over point-to-multipoint
PON	Passive Optical Network
PoW	Proof of Work
QoS	Quality of Service
R-CORD	Residential CORD
RAN	Radio Access Network
RRH	Remote Radio Head
RRU	Remote Radio Unit

SDN	Software Defined Networking
SDR	Software Defined Radio
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
SUT	System Under Test
T-CONT	Transmission Container
TC	Transmission Convergence
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TLS	Transport Layer Security
TPS	Transactions per Second
URLLC	Ultra-Reliable Low-Latency Communication
vBBU	virtualized BBU
vBMap	Virtual Bandwidth Map
VCG	Vickery-Clarke-Groves
vCPU	Virtual Central Processing Unit
vDBA	virtual DBA
VM	Virtual Machine
VNF	Virtual Network Functions
VNO	Virtual Network Operator
vOLT	virtual OLT
VULA	Virtual Unbundled Local Access
WDM	Wavelength Division Multiplexing

XG-PON	10 Gigabit PON
XGEM	XG-PON encapsulation method

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