Trustless Virtual PON Sharing for 5G Services

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***Abstract*—Sharing network/infrastructure resources becomes more essential as the cost of ownership and network deployment increases due to the new and more resource-demanding services as a part of the 5G evolution. Meanwhile, the new network ownership models challenge the conventional centralized network ownership/sharing models where a central authority is absent, leading to a trust-less market ecosystem. In this paper, we propose, for the first time, a distributed market verification mechanism using permissioned blockchain technology for multi-tenant PONs. We use the Hyperledger Fabric blockchain framework to implement our solution, which has a considerably lower cost in terms of latency and computing compared to the traditional blockchain (e.g., Bitcoin).**

***Index Terms*—Blockchain, Double Auction, Smart Contract, Virtual Network Operators.**

I. Introduction

Conventional telecommunications infrastructure ownership models are being challenged as new market players rise through the 5G evolution. This evolution involves the need for higher capacity and, therefore, higher investments in network infrastructure and, in particular, the access network, which provides the last-mile connectivity to the end-users [1]. In the fixed access network domain, Passive Optical Networks (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 [2]. PONs are fiber-optical telecommunications access network solutions that owe their popularity to high split rates, the passive nature of their optical distribution network, which does not require any active component, and their wide coverage (typically 20 kilometers and higher in Long-reach PON [3]).

PONs are one of the most widely deployed access solutions that traditionally provide broadband access using Fibre to The Home (FTTH) and Fibre to The Curb (FTTC) architectures.

The ideal situation for network sharing is an open-access model, where multiple competing Virtual Network Operators (VNOs) share a network owned by an independent third party (left-hand side of Fig. 1). In a highly dynamic resource-sharing scenario, VNOs and Infrastructure Providers (InPs) need to exchange network capacity using automatic auctioning mechanisms. For example, the InP can act as auctioneer while the VNOs can buy/sell capacity as required, e.g., to maintain the capacity and latency performance required for some of their services [4]. 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 a service provider, using the same shared infrastructure to serve its own customers (shown in the right-hand side of Fig. 1). In this more typical incumbent-based model, since the InP simultaneously operates as an auctioneer and a 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).

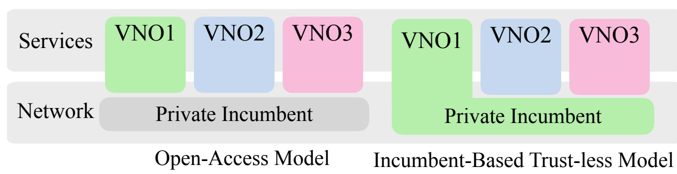

Figure 1: Access Infrastructure Sharing Models

The highly heterogeneous nature of the services and applications that 5G and beyond networks are expected to support suggests that telecom 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 the industry (Industrie 4.0 being the main framework for such scenarios). On the other hand, especially where public networks are required, network sharing across services and tenants becomes a major enabler for increasing capacity while keeping the total cost of network ownership under control [5]. 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 replacing 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 sharing wireless spectrum to data center cloud resources.In this paper, we focus on PONs, which operators are increasingly considering a suitable option for supporting the high densification scenarios envisaged by 5G and beyond networks. Precisely, we address the dynamic auctioning of PON capacity to incentivize network sharing across competing VNOs operating over the same physical infrastructure. The solution we propose for decentralizing the market is to adopt blockchain as a solution to provide:

Financial support from Irish Research Council [grant GOIPD/2020/333], Science Foundation Ireland grants 14/IA/252 (O'SHARE) and 13/RC/2077 is gratefully acknowledged. This material is based upon work supported by Google Cloud.

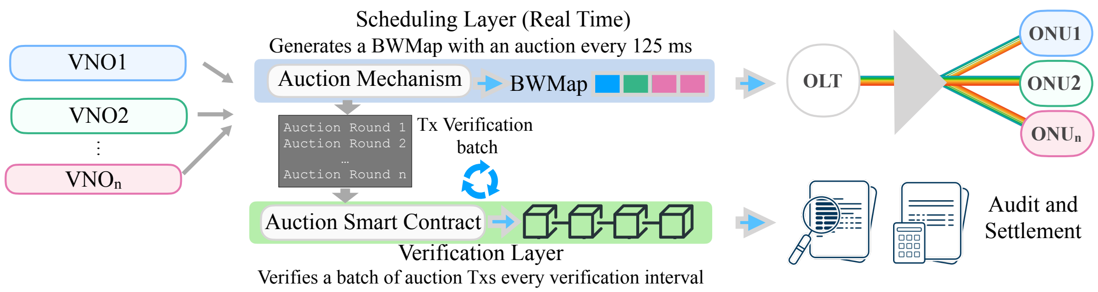

Figure 2: The Multi-Tenant PON Scheduling/Verification Model

1) Reliable and robust transaction flow provided by Blockchain consensus mechanisms such as RAFT [6].
2) Transparent transactions and record-keeping enabled by the distributed ledger technology.
3) Immutable transaction logic enabled by the smart contract technology: One party cannot unilaterally alter the terms of the contract.

Our approach is thus to run fast auctions between VNOs and InP and then run a parallel verification mechanism using a blockchain implementation on the Hyperledger Fabric 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, making the auction workable in the absence of a trusted third party.

II. Decentralizing the PON Market Mechanism

Fig. 2 shows the proposed blockchain-based verification model enhancing trust in Dynamic Bandwidth Allocation (DBA) auctions. In our model, the InP runs an auction that enables VNOs to exchange excess capacity among each other so that they can provide enhanced performance to their customers. As mentioned in [4], auctions are necessary in order to enable capacity sharing in virtualized PON environments that give VNOs full control over their capacity scheduling. The novel approach introduced in this paper enhances the centralized auctioneer with a distributed blockchain-based smart contract. In other words, while in a centralized model all the operators put trust upon the central auctioneer to decide the allocation and the price of the PON capacity, in the proposed distributed model, the auction will have to be executed and verified by all or some of the operators to be valid. However, since the scheduling in Gigabit Passive Optical Networks (GPONs) occurs every 125 μs, real-time execution of the distributed auction-based scheduling will not be feasible. This is due to the inherent latency in distributed blockchain smart contracts, as each transaction (auction) will include multiple rounds of communication/processing between the participating nodes (hosted by the organizations). This additional signaling and collaborative execution of logic will impose extra latency on the process. 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 [4]) from the blockchain-based verification step. The upstream scheduling of the PON (i.e., the scheduling

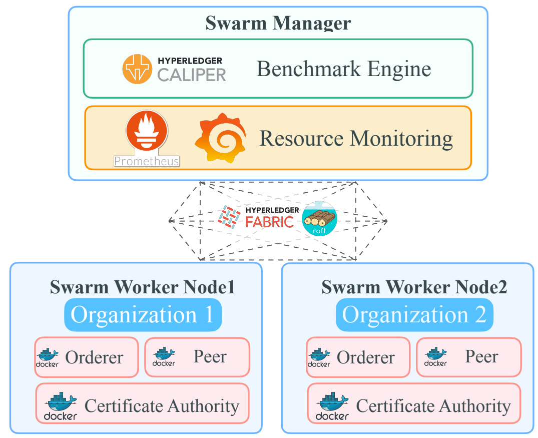

Figure 3: The PON Blockchain Network Architecture

layer in Fig. 2) will thus continue uninterruptedly while the verification layer assures correct conduct of the auction using distributed *Smart Contracts* in near-real-time.

A. *The Scheduling Layer*

The scheduling of the PON upstream transmission opportunities is executed in the scheduling layer. The VNOs send their capacity availability/demand for the next upstream frame to the scheduling layer, and the auction mechanism [4] matches the highest bidders with the cheapest sellers to release the final Bandwidth Map. 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 Bandwidth Map is then broadcasted to the Optical Networking Units (ONUs) to grant them slots in the next upstream frame. This process is repeated in real-time and fixed time periods every 125 μs in GPONs. However, as previously stated, due to network and processing latency associated with blockchain technology, the verification of transactions cannot be performed in real time.

B. *The Verification Layer*

In this paper, we propose a distributed verification layer that 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 specific pre-negotiated terms of business among stakeholders of an enterprise ecosystem. We use a private/permissioned

Table I: Numeric results of the verification experiments

Batch Size	Tx Rate/s	Min. Latency(s)	AVG. Latency(s)	Max. Latency(s)
1000	8	10.86	17.02	23.17
2000	4	0.28	0.79	1.75
4000	2	0.28	0.6	0.9
8000	1	0.76	0.78	0.91
16000	0.5	0.78	0.79	0.91
32000	0.25	0.78	0.79	0.91
64000	0.125	0.78	0.79	0.9

blockchain to deploy the verification layer. Contrary to public blockchains (e.g., Bitcoin), private blockchains support high transaction throughput and considerably lower latency. While the very fine-grained scheduling in PONs does not allow real-time verification of the auction transaction, the proposed verification layer will enable the VNOs to audit the outcome of the auctions in near-real-time (with a small delay). This delay will depend on the *Batch Size* chosen for processing the auction transactions on the smart contract. In order to allow the verification layer to process the auctions, Inequality (1) must always hold. Inequality (1) states that the transaction latency imposed by the blockchain (the time it takes for a smart contract to be executed, verified, and get written on the ledger) should be at all times lower than the batch size divided by the number of frames schedules per second ($8000/s$ in GPONs).

$$Tx\ Latency \leq \frac{BatchSize}{ScheduledFrames/S} \tag{1}$$

III. 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 blockchain nodes (Fig. 3) include three Virtual Machine (VM) instances hosted by the 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 is the Docker Swarm manager and hosts the Hyperledger Caliper [7] benchmarking tool (and the workload generator). VMs 2 and 3 (32vCPUs, 120 GB Memory) each host 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 purpose of the experiments is to identify the right value of parameters that affect the performance of the verification layer. As stated in the previous section, for seamless functioning of the verification layer, the value of the batch size parameter has to be chosen to satisfies Eq. 1. In Fig. 4 the marked area represents the area where the transaction latency is small enough to assure that the batch of auction transaction is processed before the new batch arrives from the scheduling layer. Fig. 4 illustrates the results of experiments where various batch sizes are evaluated to see the verification layer. The numerical results are reported in Table I. The sweet spot is the point in Fig. 4 where the batch size is the lowest and simultaneously while the maximum, average, and minimum transaction latency remain in the marked area that corresponds to the Eq. 1. Based on our findings and under our blockchain network setup and resource specifications, the optimal batch size is 8000, where the verification layer can receive the auction results from the scheduling layer, verify them, and write them on the distributed ledger every 1 second.

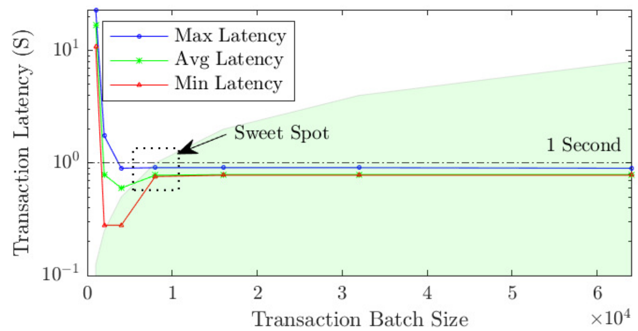

Figure 4: Batch Size V. Transaction Latency

IV. Conclusions

In this paper, we proposed distributed verification mechanism for inter-operator PON sharing marketplace to address the trust issues in conventional centralized methods. We acknowledge that due to the ultra fine-grained scheduling in PONs real-time verification of every single round of capacity auctions is unrealistic. Therefore, a near real-time alternative is proposed where a verification layer will operate parallel to the scheduling layer and process accumulated batch of auction rounds over a certain period of time and verify the contractual commitments. We developed a blockchain-based smart contract using Hyperledger Fabric and conducted experiments to determine the optimal batch size and latency associated with it. We found that our verification layer smart contract can process batch sizes of 8000 auction transactions and guarantee a delay of under 1 second.

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