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# On Design of Contracts Between Traditional MNOs and Local 5G Micro Operators

Bidushi Barua, Marja Matinmikko-Blue,  
and Matti Latva-aho

## Abstract

Local 5G networks in specific geographical areas can satisfy local capacity, coverage needs, and offer context specific services to complement Mobile Network Operator's (MNOs') offerings. For enabling the emergence of these networks into the future mobile communication market, it is necessary to determine the contractual relationships possible for different deployments of these networks. We define the features of such contracts and the factors such as competition, level of differentiation in services offered, price structure, price transparency, and the role of regulation, that will influence these contracts, taking into account the characteristics of 5G and beyond networks. A mathematical model of a pricing mechanism is proposed to determine the optimal price the local network deserves to get from the MNO and the optimal price which the MNO demands from its customers that were served by the local network. Finally, the impact of competition in the retail market, fraction of MNO customers served by the local network, on these prices are analyzed and presented using simulations. The results indicate that lower the share of MNO customers served by the 5G local network, the stronger is the incentive of the corresponding local network to increase its optimal wholesale price. Moreover, the local 5G network gains from a greater competition between MNOs as it leads to the rise in demand without the local network having to reduce the prices they demand from the MNOs for their services.

## Index Terms

Competition, contracts, micro operator networks, pricing mechanism, regulation.

## I. INTRODUCTION

The current mobile communication market is dominated by a small number of cellular *mobile network operators (MNOs)* that deploy wide area networks. Upcoming 5G networks on the

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other hand, are increasingly targeting geographically constrained areas due to the location specific usage demand characteristics and operations in higher carrier frequencies [1]. These local deployments aim to serve areas with versatile services, in specific locations such as shopping malls, hospitals, stadiums, industry plants, etc. [2], where the requirements of mobile traffic are highly versatile and constantly increasing. For such local mobile traffic, the current solution is to use Wireless Local Area Networks (WLANs) in the unlicensed bands. There have been an increasing interest by companies to deploy their own 5G networks for indoor coverage. In the future, the concept of micro operator (uO) [1] has been proposed to allow different stakeholders to deploy local 5G networks. This helps in achieving high capacities for [3] context specific services and content in these environments, to complement the MNO's offerings. The uOs need to provide flexibility, privacy, and customization in the network to serve the local needs of specific verticals, called *tenants* which are a groups of customers that are served with tailored services. One of the significant new features of uOs is network slicing [4], that helps in supporting and fulfilling diverse service requirements. The 5G local networks are deployed in such a way that a uO could serve its own restricted customer set and/or could act as a host [5] for several MNOs by providing services to their customers in a specific location.

For enabling the emergence of a large number of local 5G networks into the mobile communication market, it is necessary to define for different deployments, the contractual relationships between MNOs, uOs and tenants. We focus on defining the characteristics of service agreements [6] between the MNOs and uOs. Since uO networks share several similarities with national roaming networks [7] and networks with mobile virtual network operators (MVNOs) [8], it is natural to refer to these networks for proposing the features of contractual relationships in uO networks. In [9], different operating models and features of contracts between MNOs and MVNOs, were discussed. The work in [7], described different kinds of roaming agreements and their features. In a similar way, different possible interactions between existing MNOs and future 5G uOs are necessary to be modelled. For instance, different relationships between MNOs and uOs can defined based on the type of customers uOs is capable of serving, and/or the nature of the flow of traffic between the MNOs and uOs.

There were different factors that influenced the contractual relationships in MVNO and roaming networks. Some of these factors were competition [10], market price demand sensitivity, different shares of roaming traffic across visited networks owing to difference in coverage and

signal strength etc. [7], customers' awareness of tariffs applied for different networks [11]. For example, in [12], the authors showed that competition in roaming prices leads to the creation of a mutually beneficial relationship between the MNO and the MVNO. It is therefore important to explore and analyze the role of different factors on the contractual relationships in uO networks.

A significant purpose of designing contracts in networks is to simplify arrangements between operators by providing a framework and tariffing principles. In case of national roaming networks too, the price that MNO customers need to pay their home operators for accessing the roaming services is referred to as the *retail* price, and the price which the home operator has to pay the visitor operator, is called as the *wholesale* price [13]. In [14], different methods were proposed to determine optimal prices and profits in roaming networks. Standard Terms for International Roaming Agreement (STIRA) and Inter-Operator Tariff (IOT) were key agreements to facilitate roaming for GSM operators that pricing models for determination of optimal retail and wholesale prices in these networks. Different price setting mechanisms were used for setting up optimal prices for roaming networks depending on whether there is cooperation/no cooperation between the MNOs in [13]. In the same way, it is necessary to find a framework for the determination of optimal prices for the local 5G networks based on different levels of cooperation between MNOs and uOs.

While designing features of these contractual relationships, it is also necessary to take into consideration, the new properties of 5G networks and beyond, such as multi-tenancy [15], network slicing [4] and dynamic service-level agreement (SLAs) [16]. These aspects of uOs' service agreements with the MNOs and tenants, keeping the new features of 5G and beyond into account, have not been explored before and is therefore important to study.

The main contributions of this paper are summarized below.

- Firstly, we define different contractual relationships for different deployment models of local 5G networks, deployed by different stakeholders, taking into account the properties of future 5G networks.
- We examine the factors of competition, price structure and price transparency, and the role of regulation that will influence the contracts in local 5G networks deployed by uOs.
- We consider different methods that can be used for setting up wholesale prices based on cooperation/ non-cooperation between the MNO and the uO.
- We proposed a pricing mechanism for uOs taking into account competing forces between

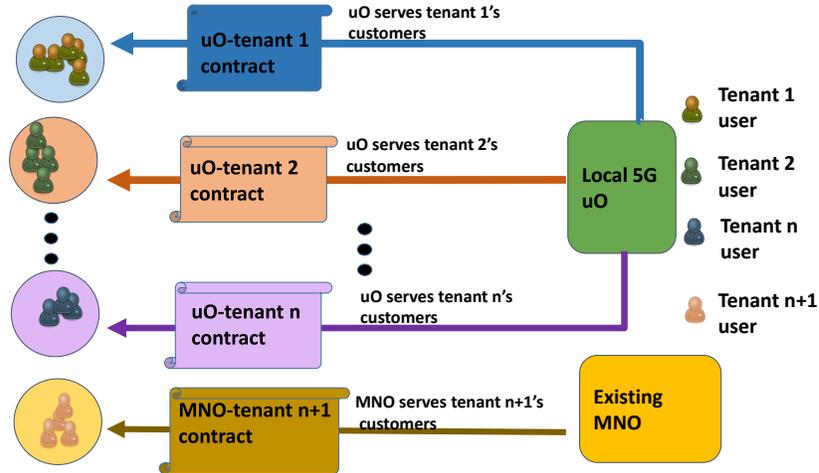


Fig. 1: Closed network relationships of uO, and users of different tenants, in presence of MNO exclusively serving tenants.

MNOs, and different shares of traffic from MNO that are served by the uO.

- Finally, we conduct a sensitivity analysis using simulations that show the effect of competition and the share of MNO's traffic that a uO serves on the optimal wholesale price according to the proposed pricing mechanism.

The rest of the paper is structured as follows. Firstly, we describe alternative uO deployments and the resulting relationships in Section II, and discuss factors that will have an influence in micro operator networks in Section III. Then in Section IV, we show different ways of determination of wholesale prices and in Section V, we propose a pricing mechanism for determination of optimal wholesale prices. In Section VI, we present simulation results for our proposed mechanism and finally in Section VII, we draw conclusions and outline possible avenues for future work.

## II. MICRO OPERATOR DEPLOYMENTS AND RESULTING RELATIONSHIPS

For the local 5G networks deployed by different kinds of uOs to enter the mobile communication market, one of the prior requirements will be for these networks to have access to spectrum resources for their operation. There are two ways in the which these networks can have access to spectrum resources. The uO can be leased out resources either by (a) the existing MNOs, or by (b) the national regulators. It is obvious that in case of option (b), the uOs can function without having any dependency on the MNOs for spectrum. When MNOs have a role in allowing entry to uOs, the MNO will voluntarily allow the uOs to enter the market only if mutually beneficial

conditions exist for both the MNOs and the uOs. However, if the MNOs abuse their market power, the regulators should in the future mandate regulations to allow the uOs to enter the market, in the same way as in networks with MVNOs [17].

Another aspect of contracts between the MNOs and uOs are the service agreements between them. For designing such agreements, it is necessary to analyze different possible deployments and their corresponding properties. Since 5G networks supports service differentiation, there is need for defining SLAs for different user groups, which makes the contract design more complicated than the contracts for previous networks. There are three deployment configurations of uO networks: closed, open, and mixed networks. We describe these deployments and their respective properties in the following sub-sections.

#### *A. Closed Network*

A closed network is here defined as a private cellular network where the users and the tenants require some authentication, for example, a private network covering a hospital. In this uO deployment, network resources are allocated to individual tenants within the network, according the services they request for (as shown in Fig. 1). Therefore, contracts need to be defined between the uOs and tenants meeting these requirements. The uOs implements network slicing and serves every tenant with network slices. This way multiple tenants are served simultaneously and with tailored services. The users of the tenants in turn pay the uO directly for the services according to the prices agreed between the tenants and the uO. The prices set up for every tenant should reflect the degree of differentiated services, the quality and locations where their services are available, etc. It is also necessary to introduce authentication methods so that only users belonging to a tenant are able to access the network slice allotted by the uO.

Alternatively, MNOs too can deploy local networks and invest to develop infrastructures that offer tailored services for a tenant. Fig. 1 shows a closed network with the contractual relationships between the uOs, MNOs and the tenants.

#### *B. Open Network*

In an open uO network deployment, the uO serves MNO customers within a locality which requires that the uO forms contracts with the MNO. For example, the MNO can buy the services from a uO instead of investing in building a network in that location. This alleviates the MNO

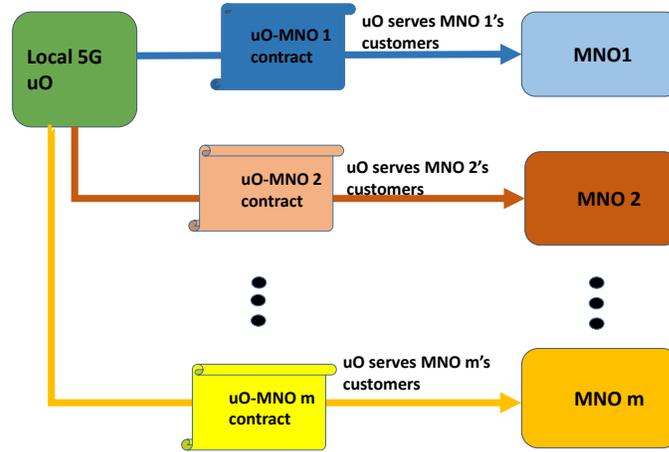


Fig. 2: Open network relationships between uOs, MNOs and customers of MNOs for agreements with unidirectional traffic flow.

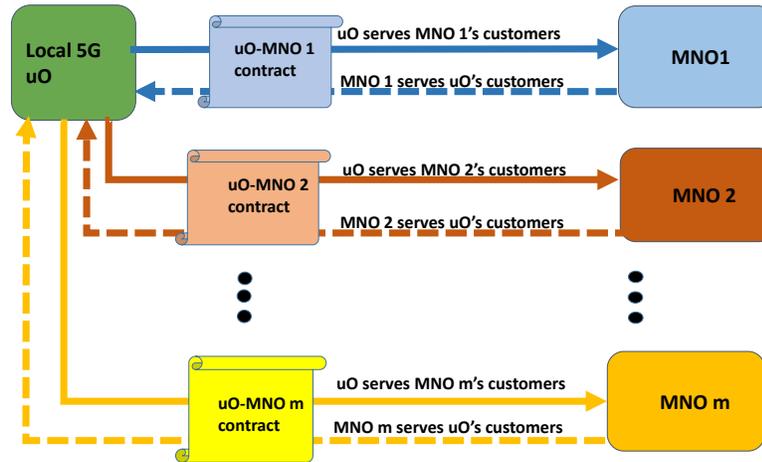


Fig. 3: Open network relationships between uOs, MNOs and customers of MNOs for agreements with reciprocal traffic flow.

from a costly investment situation. The uOs network can potentially serve the customers of a single MNO or customers of multiple MNOs. Since the customers of the MNOs are interested in the services offered by the uOs, it is necessary for MNOs to form contracts with the uOs. The uOs implements network slicing to provide network slices to different MNOs, which creates multiple contracts between the uO and the MNOs (as shown in Figs. 2 and 3). The MNOs' benefit from this relationship with uOs is good quality coverage services for its customers and savings in investments to be used for building its own network.

Due to different ways of defining contracts between the uOs and the MNOs, two configurations of open network deployments can arise. They are (a) one way access of uO's network (Fig. 2)

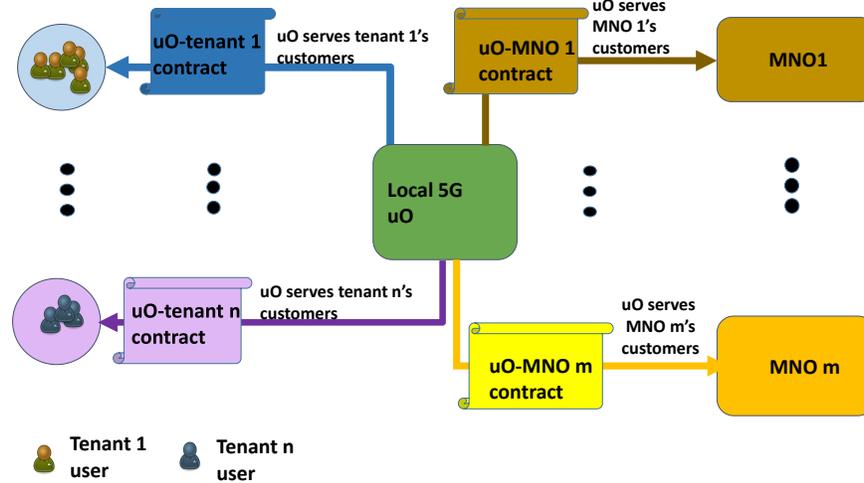


Fig. 4: Mixed network relationships between uO, MNOs, tenant users, and customers of MNOs.

and (b) two way roaming access between MNO and uO's network (Fig. 3). In one way access of uO's network, for the customers of MNO that are served by the uO, the MNO offers a wholesale payment to the uO. In two way roaming access between MNO and uO, the uO serves the customers of the MNO and its own customers has the opportunity to be served by the MNO when present within the MNO's far greater coverage area.

### C. Mixed Network

In a mixed uO network deployment, the uO serves both MNO customers and tenants within a specific area, and therefore has combined properties of open and closed networks. In these networks, contracts need to be defined between uOs, MNOs and the tenants. The uO offers different network slices to tenants and MNOs according the services they request for. The customers belonging to the tenants pay directly to the uO for the provision of network slices. On the other hand, the customers of the MNO pay the MNO directly for being served by the uO. The MNO provides the uO with a wholesale payment in return for the services offered to its customers. This deployment represents a complete and general model for networks deployed by uOs where the closed and open deployments are only the special cases of this model. A mixed uO network deployment is shown in Fig. 4.

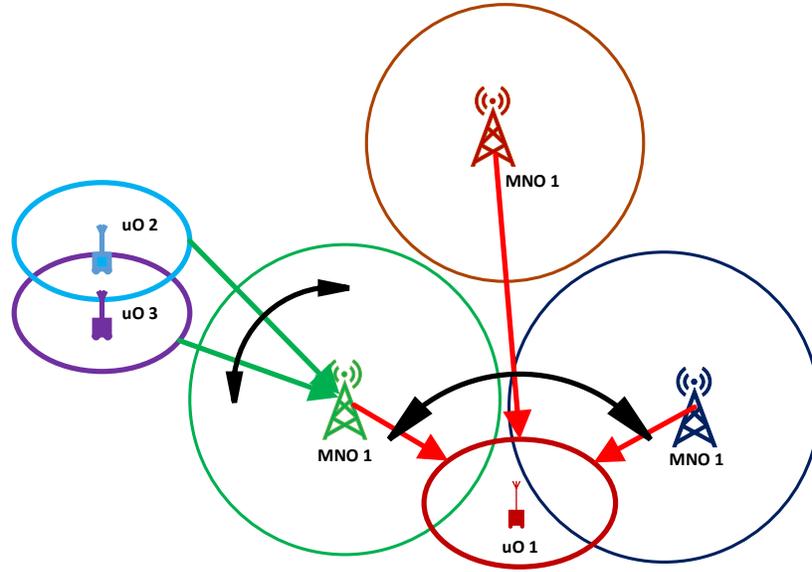


Fig. 5: Competition in micro operator networks.

### III. FACTORS INFLUENCING MNO-MICRO OPERATOR CONTRACTS

There are several factors and conditions that can influence the outcome of contracts between the MNO and the uO. In this section, we discuss a few of these factors based on previous relevant works on roaming and MVNO networks due to the similarities that these networks share with the uO networks. These factors are described as follows.

**(i) Competition:** Competition is necessary for a market to function efficiently, the lack of which can lead to negative outcomes. For example, as per a report by the international telecommunications users' association (INTUG) in 1999, due to lack of competition among operators in the wholesale international roaming market in Europe, the international wholesale roaming prices were much higher than the wholesale cost. However, with competition there is a positive influence on the retail prices, level of innovation etc. The different kinds of competition that can possibly emerge in uO networks, can potentially influence the prices which the customers need to pay, and the level of innovation in services which the customers can have access to. Mainly, two kinds of competition can occur in uO networks, which are namely (a) at the MNO level and (b) at the uO level. When a single uO can provide services to MNO customers in a specific area, several MNOs would like to avail that service by forming contracts with the concerned uO. This can be referred to as competition at the MNO level. In Fig. 5, MNOs 1, 2 and 3 compete

for the services of the uO 1. On the other hand, when several uOs can offer services to the MNO customers in a common area, there is a possibility of competition among these uOs to form contracts with MNO resulting in attracting the MNO's traffic to one of the uO's network. Competition at the uO level is illustrated in Fig. 5, where uOs 2 and 3 compete for the services of the MNO 1. In addition to the uO-MNO relationship, competition at the uO level can also impact the uO-tenant relationship. Multiple uOs in a location with different customized set of services can compete to serve the tenant users. We focus here, however, on the influence of competition among uOs, on the uO-MNO relationship.

**(ii) Modes of competition and level of service differentiation:** The mode of competition adopted and the degree of differentiated services offered by the MNOs and uOs will have a significant impact on the market performance. Competitive market dynamics have been shown to be one of the best frameworks to determine the prices for services such as roaming and/or access to MVNOs. In previous works on roaming and MVNO networks, different modes of competition have been used to approximate competition between MNOs, and/or between MNOs and MVNOs in the mobile market. Some of the common modes of competition that have been used were the Cournot [18], the Bertrand [19], and the Stackelberg [12]. The Cournot and Bertrand models refer to market models where two firms compete based on simultaneous and independent decisions on the quantity of the product and the price of the product, respectively. In contrast, in the Stackelberg game is a sequential game where a leader firm/group of firms and a follower firm/group of firms compete in terms of the quantity of the product. In [12], the authors discuss the mode of competition as MNOs' incentive to voluntarily provide network access to MVNOs. They show that MNOs invite MVNOs onto their network under Cournot competition if the market is sufficiently large. But the incentive to allow access is less in case of Bertrand competition and this declines further under Stackelberg competition. In Bertrand and Stackelberg competition, the voluntary access for MNOs network depends on the degree of product differentiation. MNOs will voluntary provide access to the MVNOs if services offered by the candidate MVNOs are sufficiently differentiated, because revenue effects outweigh the cannibalization effect, which refers to the diversion to the MVNO's services. In [20], the authors study the impact of the level of differentiation of services provided by both the MNOs and the entrant MVNOs that decides to allow entry to the MVNOs. They show that in the absence of external factors, such as coordinated price increase, capacity constraints, and regulatory interventions, (a) when the

MNOs' services are homogenous, the MNOs compete among themselves to allow access to MVNOs, (b) when the MNO's services are differentiated, both have no incentive to allow access to the MVNOs, and (c) if the MVNOs services are more differentiated as compared to the services of the MNOs, then the MVNO is allowed access only if it commits not to compete with the MNO, as facilitated by the regulatory bodies.

**(iii) Strategic decisions:** The uOs could adopt different strategies to promote competition according to the existing mobile market situation, own competitive advantages, and the needs of the customers, which will impact the contractual relationships between the MNOs and the uOs. This in turn requires the modification of contracts according to the strategy or a combination of strategies, adopted by the uOs. These strategies could be,

(a) Lower prices of services: If the uO's strategy is to offer services at low prices, all the operations of the uO are aligned to meet this target. By doing so, the uO can attract major share of MNO customers. However, to survive using this price leader strategy choice, a large customer base is required because of the small profit margins [21].

(b) Provide differentiation with content services: The uO can select to provide differentiated, value-added services for demanding customers. These service leaders might also target segments with the same services with different customized content. While competing with differentiated services the uO has the potential to earn higher revenues. Moreover, the ability to develop and provide services for the dynamic needs of the customers is advantageous for the uO [17], [21].

(c) Focussing on a narrow customer segment: The uOs can provide tailored services to a chosen segment of customers which can allow setting of a higher price for these services. Strategic alignment between the MNO and the uO that focus on niche group of customers is typically beneficial because it is not easily viable for MNOs to focus on tailored services for a small group of customers [22].

**(iii) Price structure and price transparency:** The price cap structures to be applied for uO networks is crucial while designing contracts. In the works on roaming and MVNO networks, two main price cap structures have emerged to be of significance, which are namely the volume-based and flat-rate based price cap structure. In case of the volume-based price cap structure, a fixed volume is charged with a fixed amount, whereas in flat-rate price cap for a fixed amount, the volume of data consumed has no limits [23]. In case of roaming, flat based price cap structure is a better option than volume based price structure for promoting roaming access to Internet, as

illustrated by [23]. Apart from price cap structures, the operators may choose to provide multiple tariffs for different services, or single tariff for all services, that results in a more unified pricing. Such varying pricing structures were adopted by networks with MVNOs [21].

Another significant feature for promoting the goal of increasing competition is to come up with a transparent implementation of pricing for uO's access. In previous works on international roaming [10], [24], it was observed that due to the difficulty in obtaining roaming prices, it is hard for customers to be verify or dispute bills. Customers are mostly unaware of the different rates which leads to "bill shocks". This raises the question of compliance with national legislation on pricing information and on accuracy of billing. Moreover, it discourages customers to avail the roaming services when abroad. Therefore, in uO networks actions to invoke transparency is necessary. Such transparency could be created by the delivery of tariff information by SMS [24] to the customers so that they are aware of the tariffs before being served by the uOs. In this case, the customers can take an informed and reasonable decision.

**(v) Regulatory interventions:** The policy makers or the regulatory authorities are one of the significant stakeholders, that have influenced the mobile market when market mechanisms have failed. In the past, regulators have played important roles in roaming networks and for making the entry of MVNOs viable in mobile networks. If we consider the role of regulatory in international roaming, the regulatory bodies concern was mainly on the high level of roaming charges and bill shocks [10]. However, uniform regulatory measures for diverse markets would fail to address the source of the problem and was likely to be detrimental to market performance. This could harm mobile users and the industry as a whole [25]. Strong regulations could influence the operators such that they have no incentive to invest in innovative services, which could negatively impact the services available to end users. Regulation might have resulted in short-term benefits like reduced retail prices for customers for roaming services. But this might have led to a much larger long-term reduction in the level of competition and innovation. Regulation was necessary only if there was a persistent problem, limited competition and the benefit exceeds the cost of regulation. Therefore, the industry supports a measured approach to regulation where the regulators address the structural barriers that increase costs for operators and mobile users, and the operators are encouraged to provide a transparent and uniform experience to all travellers abroad. In Europe, over the years, several directives by the European Commission were issued to reduce the roaming prices. In 2017, roaming prices were reduced to the level of the price

of other local wireless services, also called the Roam Like in Home (RLAH) [26]. Although RLAH is the most consumer-friendly option, some issues would have arose such as *permanent roaming*, which refers to the arbitrage of SIM cards from countries with low domestic prices being used in countries with high domestic prices. To avoid cases of permanent roaming under RLAH, the policy of Fair Use Limit (FUL) [27] was adopted that imposes a limit on the amount of roaming usage per customer in a certain time period, so that if the customer used roaming services beyond this limit, a surcharge had to be paid.

In case of MVNO networks, MNOs found it individually rational not to give access to MVNOs, as there lied a future threat of MVNOs absorbing a significant part of the retail market from the MNOs without possessing physical, networking or management infrastructures. In that case, the regulatory intervention was necessary for improving welfare of the network by boosting of competition [12]. In [20], the authors explain that regulators could influence the entry of MVNO into the market and improve the market performance by including *non-compete* clauses in the contracts, according to which the MVNO promises to not to compete with the MNOs when the services of the MVNO less closely resembles the services of the MNOs. An alternate way is to encourage non-discrimination remedies in contracts, where the MVNOs are prohibited from explicitly targeting the customers of the MNOs.

#### IV. MODELLING SETTING UP OF WHOLESALE PRICES IN MICRO OPERATOR NETWORKS

In a uO deployed network, different methods are applicable for setting up the wholesale prices when MNO customers have access to the services of uOs. These methods depend on the nature of traffic flow among the MNOs and uOs. For each of these traffic flow situations, the approaches that were proposed for roaming frameworks [7] under similar conditions, can be used to set up the wholesale price. These two approaches are: cooperative and non-cooperative setting up of wholesale prices and they are described below.

##### A. Cooperative setting up of wholesale prices

This method applies to a situation when the visitor uO and MNO finds a way to cooperate for determining the wholesale price that the MNO has to pay the uO. Such cooperative setting of wholesale prices are relevant for reciprocal agreements that may arise between uOs and MNOs, where the traffic flow is bi-directional. Here, both the operators need to collaborate for the

determination of common interconnection terms. A possible way of modelling this would be, to assume that the wholesale price paid by the MNO for its customers being served by the uO and the wholesale price for uO customers accessing the MNO's network, are determined in order to maximize the joint profits.

### *B. Uncooperative setting up of wholesale prices*

This method is applicable when there is no possibility of cooperation between the MNO and the uO for determination of the wholesale prices. Each visitor uO network sets a linear wholesale price to maximize its own profit. Following this each MNO sets its retail price as a mark-up on the wholesale price. The uncooperative setting up of the wholesale price can be performed by using different methods. Two such methods are (1) wholesale competition based method and (2) alliance based price setting methods.

In the wholesale competition based method, each MNO sets the retail prices as a mark-up on wholesale prices. A two-stage game can be modelled where in the first stage, each uO independently sets its wholesale price which is also called the wholesale competition, and in the second stage retail operators charge a mark-up on the wholesale price set by the uOs. In the alliance-based price setting method, the visited operator offers a discounted wholesale price to the operator that it forms an agreement with, provided that the latter sends traffic to its allied operators' infrastructures. Specifically, in case of uO networks, the uOs offer discounted wholesale prices based on the volume of traffic from the MNOs. The uO can offer a menu of wholesale tariffs consisting of a high and a low wholesale price. The low wholesale price is offered only if the MNO directs traffic to the uO, otherwise the MNO is charged with the high wholesale tariff.

## V. PROPOSED PRICING MODEL FOR MNO-UO CONTRACTS

In this section, we apply a method of determination of prices for a network with uOs, utilizing the cooperative setting up of wholesale prices, as described in Section IV. Firstly, we describe the system model based on which the MNO-uO agreement is designed. And then, we propose a pricing mechanism for the network. We assume that when customers of MNO are served by a uO in a specific region, the unidirectional traffic flow from the MNO to the uO is called the

roaming traffic of the MNO. In this case, we consider a non-cooperative approach of finding wholesale prices.

#### A. System Model of Networks with uOs

We consider a mobile market composed of two MNOs that have their distinct customer base in a region and there are two uOs that share the roaming customer base in another specific area. The MNOs compete for subscribers by offering different retail prices for accessing uO services, i.e., the price for uO's service influences the customers choice of the home MNO, which induces competition among the MNOs. The wholesale demand for uO's services is therefore influenced by price differentials because the MNO customers are aware of tariffs applicable in different uO networks. The MNOs are denoted by MNO  $i$ , where  $i = \{1, 2\}$  and the uOs are denoted by uO  $j$ , where  $j = \{a, b\}$ .

#### B. Price setting mechanism in a uO network

We focus on the MNO-uO network configuration where the customers of an MNO want services from a uO in a specific area. The uOs are offered a wholesale price by the MNO in return for the services offered to its customers. Moreover, the customers of the MNO need to pay the MNO for being served by the uO with the requested services. We address this as the retail price. We shall apply a price-setting game to set equilibrium value of these prices that maximizes individual profits of the MNO and the uO.

1) *Modelling demand:* The demand for uO's services by MNO's customers, depends on the number of customers of the MNO and the fraction of these customers that move to be under the coverage of uO. When price differences for different available uO networks are known, customers choose the visitor uO network with lower average retail prices of accessing uO's services. Therefore, the choice of home MNO network by the customers is based on the weighted average retail roaming prices set by each MNO, where the weights are determined by the distribution of MNO's traffic across visitor uO networks.

Let  $\alpha_{i,j}$  denote the share of roaming traffic of MNO  $i$  under the coverage of uO  $j$ , where  $\alpha_{i,a} + \alpha_{i,b} = 1$ .  $\alpha_{i,j}$  is determined by the signal strength and coverage of uOs network. Therefore, we can assume that  $\alpha_{1,j} = \alpha_{2,j} = \alpha_j$  for  $j = \{a, b\}$ . Let the retail price of availing the services of the uO  $j$  by the customers of MNO  $i$  be  $p_{i,j}$ . The average retail price  $p_i$  paid for roaming

services by the MNO  $i$ 's customers is the weighted average of retail prices for each possible uO network.

$$p_i = \alpha_a p_{i,a} + \alpha_b p_{i,b}. \quad (1)$$

The competition between the home MNOs on the basis of the prices customers are subjected to, for accessing the uO's services, can be modelled as a differentiated Bertrand competition [28]. The Bertrand competition describes a market that is shared by a small number of large firms, where the competing firms simultaneously (and independently) choose a price at which to sell their products/services. This type of competition leads to an efficient outcome. If products of different firms are differentiated, then consumers may not switch completely to the product with lower price. Therefore, this type of competition is used to model when the demand of a product/service by an entity depends on its own price and other firm's price. With a decrease in retail price for an MNO  $i$ , the retail demand for the service  $D_i$  increases. And with an increase in retail price for another MNO  $k$ , more consumers will opt for MNO  $i$  and the retail demand  $D_i$  would increase. Therefore, we assume that the retail demand for uO's service faced by MNO  $i$ , denoted by  $D_i$  is a linear function of its own average retail price  $p_i$  and the other MNO's average retail price  $p_k$ , as expressed below,

$$D_i = A - \beta p_i + \gamma p_k, \quad (2)$$

where  $i$  and  $k$  are two different MNOs and  $\beta = \gamma + \varepsilon$ . Here  $\gamma \geq 0$ , represents the degree of competition among MNOs based on the prices for uO's services.  $\varepsilon$  represents the overall market's price demand sensitivity. The total demand of services in uO  $j$ 's network generated by customers of MNO  $i$  is given by

$$D_{i,j} = D_i \alpha_j. \quad (3)$$

The aggregate wholesale demand faced by each uO  $j$ , denoted by  $D^j$  can be expressed in terms of the retail demands due to both MNOs, as follows

$$D^j = \sum_{i=1,2} D_i \alpha_j. \quad (4)$$

2) *Price Setting Game*: We consider *two-stage price setting game* where the MNOs and the uOs set their prices to maximize their individual profits. The price-setting game consist of

(a) stage 1, when each uO  $j$  network sets a wholesale price  $w_j$ , for providing service to the MNOs, and (b) stage 2, when each MNO  $i$  sets retail prices that the MNO will demand from its customers who have accessed the uO's services, by applying a uniform *mark-up*  $\mu_i$  to wholesale price  $w_j$ . For simplicity, we assume that the same wholesale price is expected from all MNOs by a uO  $j$ . The retail price for MNO  $i$ 's customers in uO  $j$  is equal to,

$$p_{i,j} = (1 + \mu_i)w_j, \quad (5)$$

where  $i = \{1, 2\}$  and  $j = \{a, b\}$ . The demand for uO's services depends on the average retail prices offered by the home MNOs. Therefore, using equations (1), (2) and (5), demand faced by home MNOs  $i$  is given by:

$$D_i = A - \beta(1 + \mu_i)(\alpha_a w_a + \alpha_b w_b) + \gamma(1 + \mu_j)(\alpha_a w_a + \alpha_b w_b). \quad (6)$$

The wholesale demand faced by the uO network  $j$  is a combination of demand generated by the customers of both MNO 1 and MNO 2 which wants to access the uO's services.  $D^j = \alpha_j D_1 + \alpha_j D_2$ .

This price-setting game is solved for the optimal prices using the method of backward induction, where i) firstly, the MNOs solve for optimal retail mark-ups and then ii) the uOs then set the optimal wholesale prices. The optimal retail mark-up is the mark-up that maximizes the MNO's profit. We consider the MNO's profit as a difference of revenue collected from its customers that accessed the uO's services and the wholesale payment which MNO makes to the uO. Each MNO profit is expressed by

$$\Pi_i^r = D_{ia} \cdot (p_{i,a} - w_a) + D_{ib} \cdot (p_{i,b} - w_b) \quad (7)$$

By substituting (3) and (6) in (7), we get

$$\Pi_i^r = \{A - \varepsilon(1 + \mu_i)(\alpha_a w_a + \alpha_b w_b)\} \cdot \mu_i \cdot (\alpha_a w_a + \alpha_b w_b). \quad (8)$$

The optimal retail mark-up  $\mu_i$  that will maximise  $\Pi_i^r$  is,

$$\mu_i = \mu^* = \frac{A - \varepsilon(\alpha_a w_a + \alpha_b w_b)}{(2\varepsilon + \gamma)(\alpha_a w_a + \alpha_b w_b)}, \quad (9)$$

where  $\alpha_a w_a + \alpha_b w_b$  is the weighted average wholesale price.

Secondly, the uOs find the optimal wholesale prices. The optimal wholesale price is the price that will maximize the uO's profits. We assume that each uO faces a constant marginal cost  $c$  for providing tailored services to the customers of the MNOs. The uO  $j$ 's wholesale profit is expressed as

$$\Pi_j^w = D^j \cdot (w_j - c) \quad (10)$$

By substituting the value of  $D^j$  from (6) in (10), we get

$$\begin{aligned} \Pi_j^w = & \alpha_j \{ A - \varepsilon(1 + \mu_1)(\alpha_a w_a + \alpha_b w_b) + \gamma(1 + \mu_1)(\alpha_a w_a + \alpha_b w_b) + \\ & A - \varepsilon(1 + \mu_2)(\alpha_a w_a + \alpha_b w_b) + \gamma(1 + \mu_2)(\alpha_a w_a + \alpha_b w_b) \} \cdot (w_j - c) \end{aligned} \quad (11)$$

Substituting the optimal mark-up obtained in (9), we find the optimal wholesale price that will maximize the wholesale profit of the uOs. By solving the first-order condition we obtain the optimal wholesale prices  $w_a^*$  and  $w_b^*$ :

$$w_a = w_a^* = \frac{A + \varepsilon c(3\alpha_a - 1)}{3\alpha_a \varepsilon}, w_b = w_b^* = \frac{A + \varepsilon c(3\alpha_b - 1)}{3\alpha_b \varepsilon} = \frac{A + \varepsilon c\{3(1 - \alpha_a) - 1\}}{3(1 - \alpha_a)\varepsilon}. \quad (12)$$

Therefore, using this method, we get mathematical expression for mark-up, wholesale prices that can in turn help to evaluate retail prices, demanded quantities and profits, based on the MNO-uO relationship in uO networks.

### C. Simulation results

In this section, we conduct simulations to evaluate the impact of different parameters on the optimal prices for MNOs and uOs. We perform a sensitivity analysis to understand the structure of the optimal wholesale and retail prices and the influence of those parameters on these prices.

**(a) Effect of MNO's share of traffic ( $\alpha_A$ ) served by uO A, on optimal prices:** To understand the impact of fraction of MNO's traffic that a uO has to serve, on the prices, we perform a simulation where we assume that uO A is one of the two uOs and a fraction  $\alpha_A$  of MNO's traffic is served by uO A, with a certain probability  $p$ . For this case, the optimal wholesale and mark-up price is evaluated. By taking an average of these values, we obtain the average prices and profit for a specific discrete value of share of traffic. We perform the same simulations for increasing values of traffic shares of uO A. The result is illustrated in Fig. 6(a). From this figure, we can conclude that, the average weighted wholesale price is unaffected by the distribution

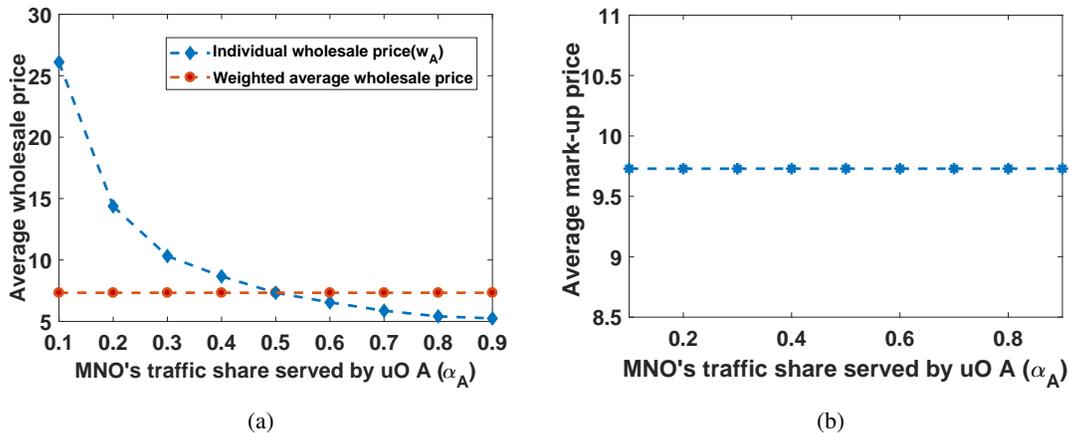


Fig. 6: (a) Comparison of average individual wholesale prices and average weighted whole prices with increasing share  $\alpha_A$  in uO A, (b) comparison of average mark-up price with increasing share  $\alpha_A$  in uO A.

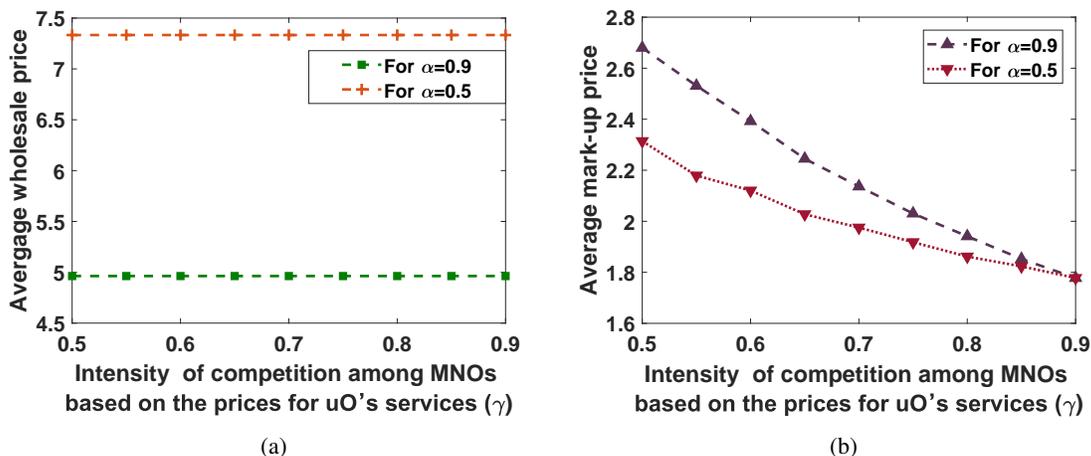


Fig. 7: (a) Comparison of average individual wholesale prices with increasing  $\gamma$ , (b) comparison of average mark-up price with increasing  $\gamma$ .

of traffic, but the average of individual optimal wholesale price decreases with increasing share of MNO's traffic served by the uO. Therefore, uOs with lower share of traffic have a stronger incentive to increase their optimal wholesale price. From Fig. 6(b), we observe that optimal mark-up prices are unaffected by the distribution of traffic between two uO networks, except for their influence on the weighted average wholesale price.

**(b) Effect of competition intensity ( $\gamma$ ) on optimal prices:** We simulate competition in the retail market of MNOs and uOs where optimal prices are evaluated. We assume that the intensity

of competition  $\gamma$  occurs with a high probability  $p$ . The optimal wholesale and mark-up price is found and an average of these values is obtained for a specific discrete value of  $\gamma$ . We perform the same simulations for increasing values of  $\gamma$ . The result is illustrated in Fig. 7 for different values of  $\alpha_A$ , where  $\alpha_A$  is the share of MNO traffic served by a uO  $A$ . From Fig. 7(a), we observe that, the optimal wholesale prices are unaffected by increasing intensity of competition in the retail market. From Fig. 7(b), it is clear that the average optimal mark-ups decrease with  $\gamma$ . Since the retail prices will decrease as a result with increasing competition, demand for uOs services will rise without the uO reducing the wholesale price. This illustrates that the uOs will benefit from a more competitive retail market.

## VI. CONCLUSION

In this paper, we studied contractual relationships arising in future due to the emergence of local 5G uO networks deployed by different stakeholders. We also study the conditions that will influence these relationships. Our focus was mainly on MNO-uO relationships in these networks. Considering the different uO network deployments, we defined the different kinds of contracts that can be designed between every MNO and uO. We also discussed the factors of competition, model of competition, level of differentiation of offered services, price transparency, and the role of regulatory, that can possibly influence these contracts. One of the significant outcome of designing contracts between the MNOs, uOs and tenants is the evaluation of optimal wholesale price which refers to the price MNO has to pay the uO for serving their customers and the optimal retail price which is the price that customers will pay the MNO for accessing the uO's services. We defined two different methods using which the wholesale prices can be set up, based on cooperation/non-cooperation between the MNOs and uOs in the price-setting process. Using one of these methods, we developed a mathematical model to represents the relationship between the MNOs and uOs, and proposed a pricing mechanism to determine the optimal wholesale and retail prices. Based on this model, a sensitivity analysis was performed to study the effect of competition intensity and share of MNO traffic that will be served by the uO, on the optimal prices.

From the results, it can be concluded that the optimal individual wholesale prices decreases with an increasing fraction of MNO customers served by the uO. Therefore, lower the share of

MNO customers served by a uO, stronger is the incentive of the corresponding uO to increase its optimal wholesale price. Another conclusion that can be drawn from the results was that, with more competition in the retail market, the optimal retail price decreases, although the optimal wholesale price remains unaffected. Therefore, the uOs gain from competition among MNOs at the retail market since it results in an increase in demand without the uOs having to reduce the wholesale price for serving the MNO customers.

In the future, this work can be expanded by considering cooperation among the MNOs and uOs to determine optimal prices which is relevant for reciprocal agreements between operators. Additionally, there is need to design a pricing mechanism that can determine optimal prices for different network slices offered by the uOs. Moreover, it is necessary to develop and analyze models to study and analyze factors other than price that can influence the contractual relationships in uO networks.

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