Strategic Network Infrastructure Sharing through Backup Reservation in a Competitive Environment

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Abstract—**In transitioning to 5G, the high infrastructure cost, the need for fast rollout of new services, and the frequent technology/system upgrades triggered wireless operators to consider adopting the cost-effective network infrastructure sharing (NIS), even among competitors, to gain technology and market access. To collaborate with competitors, NIS is a bargain whose terms and conditions need to be carefully determined to guarantee profitability in a market with uncertainties. In this work, we propose a strategic NIS framework for contractual backup reservation between a small/local network operator of limited resources and uncertain demands, and one resourceful operator with potentially redundant capacity. The backup reservation agreement requires the local operator (say, operator A) to pay a fixed reservation fee to the resource-owning operator (say, operator B) at fixed time intervals. In return, the operator B guarantees availability of its resource (e.g., spectrum) up to a predetermined level. In such a way, a certain amount of backup resource capacity is reserved for future use under high traffic demand. We characterize the bargaining between the operators in terms of the optimal reservation prices and resource reservation quantities w/o considerations of the competitions between operators in market share. The conditions under which the competitive operators will cooperate are explored. The impacts of competition intensity, redundant capacity, and demand uncertainty on performance under backup reservation are also investigated. Our study shows that NIS through backup reservation leads to both higher resource utilization and profits for operators, as well as higher service levels for end users. We also find that, under certain conditions, operator B will share its resources with operator A even at the risk of impinging on its own users, and the impact of competition intensity on the sharing decisions is highly dependent on the amount of potential redundant capacity.**

Index Terms—**Network infrastructure sharing, backup reservation, competition, game theory**

I. INTRODUCTION

In the era of 5G, as a cost-effective means for operators to quickly roll out new services, increase coverage, deploy new technologies, and improve resource utilization in a dynamic and uncertain network environment, network infrastructure sharing (NIS) has been receiving increasing interest. NIS generically refers to the sharing of network resources and elements among operators, such as spectrum, antennas, power supplies, computing and processing capacities at base stations (BSs), etc. The potential benefits of NIS have been well recognized by both wireless operators and government regulators, and its standardization and deployment is underway. For example, 3GPP LTE standard release 13 specifies several RAN (radio access network) sharing architectures to expedite new service roll-out and save system upgrade cost [1]. Many wireless operators, such as AT&T, T-Mobile, and Verizon, have participated in both passive and active network sharing. FCC has adopted new resource sharing rules for the millimeter wave spectrum among mobile systems [2]. From the 2012 report of the Presidents Council of Advisors on Science and Technology (PCAST) [3], which recommended creating "the first shared-use spectrum superhighways", new sharing approaches are continuously strongly encouraged among industry and Federal stakeholders.

While NIS has been generally recognized as beneficial, its implementation faces several challenges. Firstly, conventional models of infrastructure sharing, especially spectrum sharing in buy-in situations, are typically based on auction mechanisms. The organization and process of auctions, however, are complicated, time-consuming, and incur high overhead due to the amount of information exchanges and coordination required among the auctioneer and the bidders. As a result, auction is often considered impractical, if not infeasible, for short time scale sharing, which could have been the most desirable and useful sharing scenarios for operators dealing with dynamic and uncertain user demand. To reduce sharing overhead and ensure rapid reaction to network dynamics, new sharing models, such as those exploiting long-term contractual agreements between operators, need to be explored.

Furthermore, considering the profit-driven nature of wireless operators, the optimal amount of resources that should be shared among operators is not only an engineering decision that satisfies the QoS requirements of end users, but also an economic one that targets maximizing the profits of all participating operators. Such a decision is difficult to make beforehand, because of the uncertainties and dynamics of network traffic and channel conditions. In particular, a priori over-investment in sharing would reduce the expected economic return for operators, while under-investment cannot guarantee a satisfactory QoS during high traffic demand. As such, instead of pursuing a conventional performance-oriented stochastic resource optimization frameworks, as has been well-investigated in the literature, a novel network-economic sharing model that takes into account traffic and network uncertainties from both engineering and economic perspectives becomes indispensable.

So far, the issue of competition among operators in a NIS framework has not been well addressed. Most existing sharing models implicitly assume that the operators who are sharing resources are serving independent markets (i.e., user populations). In reality, however, competition for resources *and* end users is usually the case for operators covering the same area, and has been a key issue raised by FCC [2]. When competition is concerned, it is not yet clear whether the resource owner still has an incentive to share its resource with the competitors, as there could be a risk of losing part of its own market share. Furthermore, even when sharing takes place, how the profit, if any, should be split among the operators is also a key question that is yet to be answered.

In an attempt to address the above challenges, we propose a novel contract-based backup reservation NIS model in an uncertain and competitive market. Backup (or capacity) reservation stipulates that the operator with potential excess resources (the resource owner) will provide the operator in need (for example, a new entrant operator, NEO) with up to a predetermined quantity of the resource capacity. Depending on the actual demand, the NEO may not use the entire reserved capacity [4] (hence, the term "backup"). In that case, the owner may use the leftover capacity if needed. Such a resource sharing strategy provides substantial flexibility in handling uncertain demands, permitting better capacity and upstream resource allocation planning [5], [6], and reducing operation overhead. We study such a NIS strategy when adopted by one NEO facing uncertain demand and one operator with excess capacity. One application of our model corresponds to the popular scenario where a local operator of relatively tight resources (the NEO), such as a mobile virtual network operator (MVNO), may wish to share the resource of a resourceful national operator by signing a backup reservation contract. Note that in this paper we will focus on a pairwise contract between two operators, which is relatively simple for design and administration, but is common in the wireless industry. For example, the Ultra Mobile (a MVNO) is based on sharing contract with T-Mobile [7], and the MVNO AirVoice Wireless has sharing agreement with ATT [8]. The contract for a multi-echelon supply chain or between multiple operators should consider more complex business relationships and bargaining powers, which is beyond the scope of this paper.

The main contributions of this paper are four-fold:

First, to provide more flexibility into NIS and better combat demand/supply uncertainty, we introduce the concept of backup reservation into the sharing game and design a novel contract to support efficient and profitable NIS. The equilibrium contract parameters related to the operators' sharing decisions under demand uncertainties are obtained.

Second, to consider the issue of the incentive of cooperation in competitive market environments, we provide a co-opetitive NIS framework. The conditions under which operators will benefit from such a resource sharing policy are examined, which include the competition intensity between operators, the service price and level, and the variance in demands facing the operators. Our work is among the first to compare NIS decisions under independent and competitive market scenarios.

Third, to motivate the operators to engage in NIS and simultaneously provide better wireless service, we further evaluate the interactions between two markets: the wireless service market in satisfying subscribers' traffic demand and the network resource market in relation to resource trading. In contrast to prior works that view the network infrastructure market separately from the wireless service market, to the best of our knowledge, this paper is the first attempt to quantitatively analyze how the sharing scheme in resource market enhances the service level in the service market and how competition in service markets affects the resource trading decisions.

Finally, in contrast to the finding in [9] in which the authors concluded that setting aside resources (e.g., spectrum) exclusively for secondary users will likely impinge on the current users of the primary system and may not be in the interest of its business model, we show that under backup reservation contract, when the NEO's service price charged to the subscribers in using one resource unit is higher than that of the owner's, the owner will be even likely to lose its current users to get more revenue from sharing the resource. Quantitatively, we find that under the competitive scenario, whether the operators can benefit from the sharing scheme depends on four key variables: the redundant capacity, the service prices per unit resource capacity, the resource utilization or service levels, and the competitive intensity. Our numerical results also reveal that NIS through backup reservation leads to both higher resource utilization and higher service level for NEO's users. And its benefit for the whole system is higher under the competitive scenario.

Our findings provide insights on the engineering and economic aspects of NIS, and could contribute to a guideline for operators to determine their NIS partners and contracts that lead to an efficient and profitable cooperation in a volatile and competitive market. The study provides a better understanding on how to implement NIS practically and by shedding insights on the value of a backup supply in NIS.

The remainder of this paper is organized as follows. We describe the system model and formulate the problem in Section II. Sharing decisions in independent and competitive markets are presented in Sections III and IV, respectively. Section V presents the numerical results. We review related work in Section VI and draw conclusions in Section VII.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Overview

We consider a NEO with none or limited network resource capacity, providing wireless network services in n service areas. Its potential number of users is stochastic and therefore the average traffic demand is uncertain. At a target service level decided by the NEO, if its limited capacity cannot satisfy the total realized demand, the unsatisfied customers will be lost or migrate to the competitors. To ensure responsive capacity and mitigate demand risks, the NEO signs a backup reservation contract with a wireless service provider who has sufficient resource (the resource-owning operator ROO). In the contract, the NEO reserves a certain amount of resource capacity from the ROO at a reservation price in advance, and then uses the resource to satisfy its own subscribers when needed, as illustrated in Fig. 1. This type of reservation contract provides more and flexible resource for the NEO, and the ROO is supposed to benefit from the infrastructure sharing for higher capacity utilization and a new revenue source. Note that the NEO and its subscribers have a higher priority in using the reserved capacity over the ROO's own subscribers, and therefore the ROO may experience capacity starvation and partial customer loss under high traffic demand if it overly commits its capacity to the reservation. This requires the ROO to carefully decide its reservation contract to ensure a profitable sharing.

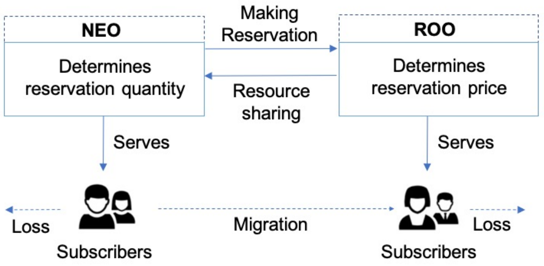


Fig. 1. The backup reservation scheme between the operators

B. The Operators' Resource Capacity

In the i-th serving area, the NEO's network resource capacity is denoted as $M_i^{(V)}(i=1,\cdots,n)$. This capacity may be zero or viewed as the resource capacity that the operator has already leased from other operators.

We consider a ROO as a wireless service provider already long existing in its service areas, who has developed a group of loyal customers or comparatively stable expected demand (therefore assumed constant in our model). Besides, it has sufficient resource capacity to meet its constant potential demand. Denote its total resource capacity as $M_i^{(R)}$ and the possible redundant capacity as S_i in each service area. As in [10], the notion of an infrastructure is quite general, composed of resources such as links, servers, and buffers, and the quantity of the infrastructure might be the bandwidth of a communication link or the cycles available in a computational grid. For instance, we can view the capacity amount as the number of network slices in a 5G network.

C. Target Service Level

At the beginning of every selling season, the NEO needs to determine its target service level, i.e., the average number of subscribers, $l^{(V)}$, that will share one unit of resource capacity. For example, the operator may decide that an average traffic demand of five subscribers are going to be satisfied by one unit of network slice ($l^{(V)}=5$). The subscribers' satisfaction level is therefore highly dependent on its value. In the following analysis, we will use $\frac{1}{l^{(V)}}$ to indicate the service level. The smaller value $l^{(V)}$ has, the higher service levels the subscribers experience. Note that the above service model is meant to be general. It does not assume any particular medium access control (MAC) protocol, but instead captures the basic behavior of all MAC mechanisms, i.e., the service level enjoyed by a subscriber deteriorates with the number of subscribers accessing the same amount of resource. Besides, this target service level is announced by the operator to the market as an average service level, not the level throughout all the service time for the subscribers. So it is reasonable that when there is a traffic demand burst from the subscribers, the instant service level can be lower.

If we use $U(l^{(V)})$ to measure the users' average satisfaction level, it is reasonable to assume that $\frac{dU}{dl^{(V)}}<0$, $\frac{d^2U}{dl^{(V)2}}<0$. For example, if one band of spectrum is shared among an average of $l^{(V)}$ users, the average data rate can be written as $\ln(1+\frac{P}{n_0+P(l^{(V)}-1)})$, where P is the average received power and n_0 is the noise power. The users' satisfaction level can be defined as an increasing function of the difference between the achievable data rate and the users' data rate requirement, e.g., $U(l^{(V)})=\frac{1}{1+e^{-h[\ln(1+\frac{P}{n_0+P(l^{(V)}-1)})-\ln(1+\frac{P}{n_0+P(l^{(V)}_{\max}-1)})]}}$, where $l^{(V)}_{\max}$ is the maximum value of $l^{(V)}$, which indicates the lowest service level the subscribers can accept; and h decides the steepness of the satisfactory curve [11]. We suppose $l^{(R)}$, a constant, is the average number of subscribers sharing one unit resource in the ROO's market strategy.

D. Service Pricing

For each subscriber, the NEO charges a unit service price of $p_c^{(V)}$ per selling cycle. This is equivalent to an average price per resource that can be written as $p_r^{(V)}=l^{(V)}p_c^{(V)}$. The service price can be explained as the highest acceptable price by the subscribers for the service, and normally increases with the service level. It is reasonable to suppose that $p_c^{(V)}=\alpha U(l^{(V)})$ where α is the equivalent revenue per degree of users' satisfaction. This assumption is similar to that in [11], which characterizes the linear relationship between the user's satisfaction degree and its overall utility.

Therefore, there is a trade-off for the NEO to make a decision on the target service level: higher service level indicates more resources to be needed, which implies larger customer lost rate with limited resource capacity, but also larger unit price and revenue. In providing the wireless service, the ROO's service price is $p_r^{(R)}$ per unit resource.

E. Demand Uncertainty and Lost Demand

On the NEO's side, the number of its potential subscribers is stochastic in each service area, denoted as $x_i^{(c)}$ per cycle. Under a service level denoted by an average number of $l^{(V)}$ subscribers sharing one unit resource, the total resource demand in each area can therefore be written as $x_i=x_i^{(c)}/l^{(V)}$ units per cycle, which is assumed to follow a distribution with cumulative distribution function $F_i(\cdot)$, probability density function of $f_i(\cdot)$ and a mean of μ_i. This distribution is dependent on both the distribution of the user number $x_i^{(c)}$ and the service level. For instance, if $x_i^{(c)}$ follows uniform distribution $U(a_0,b_0)$, then x_i follows $U(a_0/l^{(V)},b_0/l^{(V)})$.

If the NEO's limited resource cannot satisfy all the coming customers at the target service level, then a part of the customers will be lost or may turn to its competitor, the ROO. By lost demand, we mean the corresponding demand of customers that cannot sign service agreements with the operator upon arriving. The lost rate can be expressed as $1-\frac{the\ actual\ number\ of\ subscribers}{the\ number\ of\ arriving\ customers}$. Similar to [12], the demand we considers is a long-term average demand that is independent of short-term wireless characteristics. That is, a burst of customers in a selling cycle may cause larger customer lost rate; while a burst of data traffic demand among the subscribers would not incur any demand loss.

As for the ROO who has built a stable customer base, the number of potential customers is assumed to be constant and can be calculated as $(M_i^{(R)}-S_i)l^{(R)}$.

F. Backup Reservation Scheme and Problem Formulation

As a condition of the backup reservation contract, the NEO will pay a fixed monetary amount $w_{ri}R_i$, regardless of the actual amount of resources to be used in the cycle. R_i is the reserved capacity level for each service area chosen by the NEO. If the NEO's current resource capacity can meet the realized resource demand, no backup resource from the resource-owning operator is needed; otherwise the NEO should use the reserved resource at the ROO. Note that for the redundant capacity S_i, the ROO may or may not require the NEO to reserve before using, which depends on the market situations that we will specify later.

The sequence of events proceeds as follows: (i) stage 1: at the beginning of each marketing-planning period (the duration of which is decided by the NEO's long-term plan for the market strategy and the service contract duration, e.g. one year), the NEO selects its target market by determining its service level and the corresponding service price. This is set in the first stage as a high-level market positioning strategy; (ii) stage 2: knowing the NEO's target market, the ROO sets the unit reservation price w_{ri} for the whole period by considering their possible competition in that market segment, and announces it to the NEO; (iii) stage 3: then the NEO determines its reservation quantity R_i as a response and pays the ROO a monetary amount $w_{ri}R_i$ in each selling cycle (e.g., one month) within its market-planning period; (iv) stage 4: after the demand (the actual number of customers, thus the expected average demand of resource) at the NEO in each selling cycle is realized, he/she determines the quantity of reserved resources to be used in this cycle at a unit capacity usage fee of w ($w < \min\{p_r^{(R)}, p_r^{(V)}\}$), which is exogenously determined by the resource market. If the reserved part of the resources is not used by the NEO, the ROO can still use them to satisfy its own traffic demand; but if the NEO uses them, higher priority should be given to the NEO than its own users; and finally (v) demands are satisfied, or the potential customers are lost when the operators cannot sign the agreements with some of the coming customers due to the lack of resource for target service level. We aim to answer the following questions:

1) How would the reservation-based sharing scheme affect the NEO's service level and expected profit?
2) Can both operators benefit from the backup reservation? When does the NEO prefer not to make any reservation? Or when does the ROO reject the reservation request? How does the redundant capacity at the ROO affect the reservation price and the reservation quantity?
3) If the service markets are competitive, do the operators still benefit from backup reservation? How does the market competition intensity affect the results?

III. SHARING DECISIONS WITH INDEPENDENT MARKETS

In this section, as a benchmark, we first consider the scenario in which the operators respectively provide service for two completely independent markets. To analyze the decisions and benefits of backup reservation, we consider two cases: i) the NEO does not reserve, and the shared resource quantity from the ROO should not exceed S_i, and ii) if the NEO would like to share more than S_i, he/she needs to reserve in advance for the extra part. In this case, when the resource demand is larger than $M_i^{(V)}$, a total resource quantity of $R_i + S_i$ can be shared for each serving area if needed. We suppose the NEO's demand distribution is known to the ROO through market investigation. The problem under asymmetric information can be solved through contract design with different sets of prices and reservation quantities. By satisfying both individual rationality and incentive compatibility constraints in moral hazard models, the NEO would truthfully reveal its private demand information, as studied in [10]. Here we will focus on the contract design under symmetric information which is widely assumed as in literature as [9], [12], [13].

A. Utility Functions

1) Without Backup Reservation: In the case of no backup reservation, the users that cannot be satisfied with resources of $M_i^{(V)} + S_i$ at the NEO are simply lost.

With an average number of $l^{(V)} \int_{M_i^{(V)}+S_i}^{+\infty} (x_i - M_i^{(V)} - S_i) f_i(x_i) dx_i$ customers lost due to resource scarcity in each area, the NEO's expected profit can be written as

$$\begin{aligned}\Pi_1^{(V)} = \sum_{i=1}^{n} [&-w \int_{M_i^{(V)}}^{M_i^{(V)}+S_i} (x_i - M_i^{(V)}) f_i(x_i) dx_i \\ &- wS_i \int_{M_i^{(V)}+S_i}^{+\infty} f_i(x_i) dx_i + \mu_i p_r^{(V)} \\ &- p_r^{(V)} \int_{M_i^{(V)}+S_i}^{+\infty} (x_i - M_i^{(V)} - S_i) f_i(x_i) dx_i]\end{aligned} \tag{1}$$

The NEO's decision is represented as $l_1^{(V)*} = \arg\max \Pi_1^{(V)}$, where $l_1^{(V)} \leq l_{\max}^{(V)}$. Similarly, the ROO's expected profit is

$$\begin{aligned}\Pi_1^{(R)} = \sum_{i=1}^{n} [&(M_i^{(R)} - S_i) p_r^{(R)} + wS_i \int_{M_i^{(V)}+S_i}^{+\infty} f_i(x_i) dx_i \\ &- w \int_{M_i^{(V)}}^{M_i^{(V)}+S_i} (x_i - M_i^{(V)}) f_i(x_i) dx_i]\end{aligned} \tag{2}$$

2) With Backup Reservation: When the NEO reserves R_i units of resources and the ROO accepts the reservation requests, the NEO's expected profit is given by

$$\begin{aligned}\Pi_2^{(V)} = \sum_{i=1}^{n} [&-w_{ri} R_i + \mu_i p_r^{(V)} \\ &- p_r^{(V)} \int_{M_i^{(V)}+S_i+R_i}^{+\infty} (x_i - M_i^{(V)} - S_i - R_i) f_i(x_i) dx_i \\ &- w(S_i + R_i) \int_{M_i^{(V)}+S_i+R_i}^{+\infty} f_i(x_i) dx_i \\ &- w \int_{M_i^{(V)}}^{M_i^{(V)}+S_i+R_i} (x_i - M_i^{(V)}) f_i(x_i) dx_i],\end{aligned} \tag{3}$$

In the following analysis, we do not consider the case when the possible highest demand is smaller than $M_i^{(V)} + S_i$. The expected profit of the ROO consists of three parts: the reservation cost, the revenue earned through sharing resources and the revenue of providing services to its own subscribers.

$$\begin{aligned}\Pi_2^{(R)} = \sum_{i=1}^{n} [&w_{ri} R_i + w \int_{M_i^{(V)}}^{M_i^{(V)}+S_i+R_i} (x_i - M_i^{(V)}) f_i(x_i) dx_i \\ &+ w(S_i + R_i) \int_{M_i^{(V)}+S_i+R_i}^{+\infty} f_i(x_i) dx_i \\ &+ p_r^{(R)} \int_{M_i^{(V)}+S_i}^{M_i^{(V)}+S_i+R_i} (R_i - (x_i - M_i^{(V)} - S_i)) f_i(x_i) dx_i \\ &+ R_i p_r^{(R)} \int_{0}^{M_i^{(V)}+S_i} f_i(x_i) dx_i + p_r^{(R)} (M_i^{(R)} - S_i - R_i)]\end{aligned} \tag{4}$$

B. Stackelberg Game and Equilibrium Solution Analysis

It is straightforward to see that the optimal usage amount for the NEO in a selling cycle is $\min\{(x_i - M_i^{(V)})^+, S_i + R_i\}$. To make optimal decisions, a three-stage stackelberg game is employed to describe the results of the bargaining process. We adopt backward induction to derive the equilibrium solution in three stages. First, in stage 3: given the service level, we derive the optimal reservation quantities of the NEO; second, with the prediction of the NEO's response, the ROO's decision of unit reservation price is analyzed in stage 2; finally, we consider stage 1, where the NEO determines the optimal service level.

Stage 3: The NEO sets the reservation quantity

Given the service level and the reservation price, By maximizing the NEO's expected profit in (3), we have:

Lemma 1. In independent markets with decentralized operators, given the reservation price w_{ri} and the service level, the optimal reservation quantity satisfies

$$R_i^* = \max\{\min\{F_i^{-1}(1 - \tfrac{w_{ri}}{p_r^{(V)} - w}) - S_i - M_i^{(V)}, M_i^{(R)} - S_i\}, 0\} \tag{5}$$

Proof: the proof of lemma 1 (and also for all the other lemmas and propositions in this paper) is provided in our online technical report [14]. The detail of the proof is omitted here due to the space limit.

Stage 2: The ROO sets the reservation price

The ROO needs to decide the optimal reservation price to maximize its expected profit. If it does not expect to share more resource than its redundancy S_i, it will set $w_{ri} = (p_r^{(V)} - w) \int_{M_i^{(V)} + S_i}^{+\infty} f_i(x_i) dx_i$; otherwise, an optimal value of w_{ri} will be given with the consideration of the NEO's response shown in (5). And the following result can be obtained:

Proposition 1. In independent markets with decentralized operators, suppose the optimal reservation quantity is smaller than $M_i^{(R)} - S_i$, then the optimal value of unit reservation price w_{ri} should satisfy

$$R_i(w_{ri})(p_r^{(V)} - w)^2 f_i(M_i^{(V)} + S_i + R_i(w_{ri})) = w_{ri}(p_r^{(V)} - p_r^{(R)}) \tag{6}$$

where $R_i(w_{ri}) = F_i^{-1}(1 - \frac{w_{ri}}{p_r^{(V)} - w}) - M_i^{(V)} - S_i$.

From (6), the ROO is always better off under backup reservation in the independent markets as long as $p_r^{(V)} > p_r^{(R)}$.

Stage 1: The NEO sets the service level

When the predictions of R and w_r are made, the NEO needs to determine the optimal value of $l^{(V)}$ or $p_r^{(V)}$, denoted as

$$\begin{aligned} l_2^{(V)*} &= \arg\max \Pi_2^{(V)} \\ s.t.\ l_2^{(V)} &\leq l_{\max}^{(V)} \end{aligned} \tag{7}$$

Since $p_r^{(V)} = l^{(V)} p_c^{(V)}(l^{(V)}) = l^{(V)} \alpha U(l^{(V)})$, $\frac{dp_r^{(V)}}{dl^{(V)}} = p_c^{(V)}(l^{(V)}) + l^{(V)} \frac{dp_c^{(V)}(l^{(V)})}{dl^{(V)}}$, $\frac{d^2 p_r^{(V)}}{dl^{(V)2}} = l^{(V)} \frac{d^2 p_c^{(V)}}{dl^{(V)2}} + 2\frac{dp_r^{(V)}}{dl^{(V)}} < 0$, we can find a range of $[l_A^{(V)}, l_B^{(V)}]$ within which $p_r^{(V)} \geq p_r^{(R)}$ can be satisfied, where $l_A^{(V)}$ or $l_B^{(V)}$ satisfies $p_r^{(V)} = p_r^{(R)}$. If $l_A^{(V)} = l_B^{(V)}$, then no backup reservation is made.

It is intuitive that, with the backup reservation scheme, more resources are available, which encourages the NEO to provide higher level services. After incorporating equation (5), due to the complexity of the function, it is hard to show the closed form of $l^{(V)*}$. We will further evaluate the impacts of the backup reservation scheme on the service level in details through the numerical analysis in Section V. The algorithm for calculating the optimal value of $l^{(V)}$ is listed as follows:

Step 1) Calculate the thresholds of making backup reservation $p_r^{(V)} \geq p_r^{(R)} : l^{(V)} \in [l_A^{(V)}, l_B^{(V)}]$;

Step 2) For $l^{(V)} \notin [l_A^{(V)}, l_B^{(V)}]$, find $l_1^{(V)*} = \arg\max \Pi_1^{(V)}$, if $l_1^{(V)*} > l_{\max}^{(V)}$, then $l_1^{(V)*} = l_{\max}^{(V)}$;

Step 3) For $l^{(V)} \in [l_A^{(V)}, l_B^{(V)}]$, first calculate the value of R_i and w_{ri} using (5) and (6), then combine them with (3), and find $l_2^{(V)*} = \arg\max \Pi_2^{(V)}$, if $l_2^{(V)*} > l_{\max}^{(V)}$, then $l_2^{(V)*} = l_{\max}^{(V)}$;

Step 4) Compare $\Pi_1^{(V)}|_{l^{(V)} = l_1^{(V)*}}$ and $\Pi_2^{(V)}|_{l^{(V)} = l_2^{(V)*}}$, select the one with larger value for the final expected profit, and the corresponding $l^{(V)}$ as the optimal solution.

IV. SHARING DECISIONS BETWEEN COMPETITIVE OPERATORS

In the competitive markets, if the users cannot be satisfied by the NEO, some of them may migrate to another market [15]. This happens when the two operators provide different but similar wireless services, and each has its own potential customers. The unsatisfied customers choose an alternative source of service supply only when the primary supplier is out of stock. We assume the percentage of unsatisfied customers that switch to the ROO is k ($0 < k \leq 1$), which measures the competition intensity between the operators [16], with $k = 1$ indicating the highest competition intensity. We still assume that the ROO has a redundant capacity of S_i after satisfying his own subscribers. But the redundant capacity can be used later to satisfy the new demand coming from the NEO's market. In this case, the ROO may not benefit from the backup reservation since the lost demand at the ROO would turn to it. Therefore, we consider the situation when the NEO needs to make a backup reservation first before sharing any amount of resource, including the potential redundant capacity, and examine the conditions under which a backup reservation scheme benefit both operators.

A. Utility Functions

1) Without Backup Reservation: If no reservation is made at the ROO, the NEO only has his own resources. The NEO's decision is $l_1^{(V)*} = \arg\max \Pi_1^{(V)}$, where $l_1^{(V)} \leq l_{\max}^{(V)}$, and

$$\Pi_1^{(V)} = p_r^{(V)} \sum_{i=1}^{n} [\int_0^{M_i^{(V)}} x f_i(x_i) dx_i + M_i^{(V)} \int_{M_i^{(V)}}^{+\infty} f_i(x_i) dx_i] \tag{8}$$

The ROO's expected profit is

$$\begin{aligned} \Pi_1^{(R)} = {} & (M_i^{(R)} - S_i) p_r^{(R)} + p_r^{(R)} S_i \int_{M_i^{(V)} + \frac{S_i}{k\beta}}^{+\infty} f_i(x_i) dx_i \\ & + k\beta p_r^{(R)} \int_{M_i^{(V)}}^{M_i^{(V)} + \frac{S_i}{k\beta}} (x_i - M_i^{(V)}) f_i(x_i) dx_i. \end{aligned} \tag{9}$$

where $\beta = l^{(V)}/l^{(R)}$ indicates the difference between the two operators' service level.

2) With Backup Reservation: For the NEO, the actual number of lost customers in one selling cycle is $l^{(V)}(x_i - M_i^{(V)} - R_i)^+$, and the actual usage amount of resources shared from the ROO is $\min\{(x_i - M_i^{(V)})^+, R_i\}$. Then the expected profit of the NEO can be written as

$$\begin{aligned}\Pi_2^{(V)} = \sum_{i=1}^{n} [& p_r^{(V)} \int_0^{M_i^{(V)}+R_i} x_i f_i(x_i) dx_i \\ & + p_r^{(V)} \int_{M_i^{(V)}+R_i}^{+\infty} (M_i^{(V)} + R_i) f_i(x_i) dx_i - w_r R_i \\ & - wR_i \int_{M_i^{(V)}+R_i}^{+\infty} f_i(x_i) dx_i \\ & - w \int_{M_i^{(V)}}^{M_i^{(V)}+R_i} (x_i - M_i^{(V)}) f_i(x_i) dx_i].\end{aligned} \tag{10}$$

As for the ROO, two cases need to be considered:
Case 1: $R_i \leq S_i$

$$\begin{aligned}\Pi_{2i}^{(R)} = & (M_i^{(R)} - S_i) p_r^{(R)} + w_{ri} R_i + wR_i \int_{M_i^{(V)}+R_i}^{+\infty} f_i(x_i) dx_i \\ & + w \int_{M_i^{(V)}}^{M_i^{(V)}+R_i} (x_i - M_i^{(V)}) f_i(x_i) dx_i \\ & + k\beta p_r^{(R)} \int_{M_i^{(V)}+R_i}^{M_i^{(V)}+R_i+\frac{S_i-R_i}{k\beta}} (x_i - M_i^{(V)} - R_i) f_i(x_i) dx_i \\ & + p_r^{(R)} \int_{M_i^{(V)}+R_i+\frac{S_i-R_i}{k\beta}}^{+\infty} (S_i - R_i) f_i(x_i) dx_i,\end{aligned} \tag{11}$$

Case 2: $R_i > S_i$

$$\begin{aligned}\Pi_{2i}^{(R)} = & (M_i^{(R)} - R_i) p_r^{(R)} + wR_i \int_{M_i^{(V)}+R_i}^{+\infty} f_i(x_i) dx_i \\ & + p_r^{(R)} \int_0^{M_i^{(V)}+S_i} (R_i - S_i) f_i(x_i) dx_i \\ & + p_r^{(R)} \int_{M_i^{(V)}+S_i}^{M_i^{(V)}+R_i} (R_i - x_i + M_i^{(V)}) f_i(x_i) dx_i + w_{ri} R_i \\ & + w \int_{M_i^{(V)}}^{M_i^{(V)}+R_i} (x_i - M_i^{(V)}) f_i(x_i) dx_i.\end{aligned} \tag{12}$$

And the ROO's total expected profit is $\Pi_2^{(R)} = \sum_{i=1}^{n} \Pi_{2i}^{(R)}$.

B. Stackelberg Game and Equilibrium Solution Analysis

Similar to the procedures of decision-making under independent markets, in the following models, we derive the stackelberg equilibrium solution in stage 3&2 first and then analyze the NEO's optimal service level in stage 1.

Stage 3: The NEO sets the reservation quantity

By maximizing the NEO's expected function of (10), the optimal reservation quantity when w_{ri} is given can be derived:

Lemma 2. In competitive markets with decentralized operators, given the service level of the NEO and the reservation price w_{ri}, the optimal reservation quantity satisfies

$$R_i^* = \max\{\min\{F_i^{-1}(1 - \frac{w_{ri}}{p_r^{(V)} - w}) - M_i^{(V)}, M_i^{(R)}\}, 0\} \tag{13}$$

Compared with (5), the only difference is that the ROO's potential redundant capacity S_i does not affect the NEO's reservation quantity in the competitive markets. This result is intuitive because the ROO may have no capacity left when it might need to satisfy new demand coming from the NEO's market. And for $R_i > 0$, we need $w_{ri} < (p_r^{(V)} - w) \int_{M_i^{(V)}+S_i}^{+\infty} f_i(x_i) dx_i$. Compare this condition with that in independent markets: $w_{ri} < (p_r^{(V)} - w) \int_{M_i^{(V)}+S_i}^{+\infty} f_i(x_i) dx_i$, the need of the NEO to make a reservation under the competitive scenario is apparently higher.

Stage 2: The ROO sets the reservation price

By substituting R_i in (11) and (12) with (13), and setting $\frac{d\Pi_{2i}^{(R)}}{dR_i} = 0$, the following result can be obtained.

Proposition 2. In competitive markets with decentralized operators, the optimal reservation price w_{ri} belongs to $\{(1 - F_i(M_i^{(V)}))(p_r^{(V)} - w), w_{ri1}, (1 - F_i(S_i + M_i^{(V)}))(p_r^{(V)} - w), w_{ri2}, (1 - F_i(M_i^{(R)} + M_i^{(V)}))(p_r^{(V)} - w)\}$. The NEO makes no reservation in the i-th area when $w_{ri} \geq (1 - F_i(M_i^{(V)}))(p_r^{(V)} - w)$, and makes maximum reservation when $w_{ri} \leq (1 - F_i(M_i^{(R)} + M_i^{(V)}))(p_r^{(V)} - w)$, where w_{ri1} satisfies

$$\begin{aligned}R_i(w_{ri})(p_r^{(V)} - w)^2 f_i(M_i^{(V)} + R_i(w_{ri})) = w_{ri}(p_r^{(V)} - p_r^{(R)}) \\ + p_r^{(R)}(1 - k\beta)(p_r^{(V)} - w) \int_{M_i^{(V)}+R_i}^{M_i^{(V)}+R_i+\frac{S_i-R_i}{k\beta}} f_i(x_i) dx_i,\end{aligned} \tag{14}$$

w_{ri2} satisfies

$$w_{ri}(p_r^{(V)} - p_r^{(R)}) = R_i(w_{ri})(p_r^{(V)} - w)^2 f_i(M_i^{(V)} + R_i(w_{ri})), \tag{15}$$

and $R_i(w_{ri}) = F_i^{-1}(1 - \frac{w_{ri}}{p_r^{(V)} - w}) - M_i^{(V)}$.

Furthermore, the following results can be derived.

Proposition 3. In competitive markets with decentralized operators, if $p_r^{(V)} < p_r^{(R)}$ and $k\beta > 1$, then the ROO will set a high reservation price that no reservation is made from the NEO.

Specifically, if the user number follows uniform distribution:

Proposition 4. In competitive markets with stochastic customer number following uniform distribution $U(a_i, b_i)$ at the NEO, both operators will benefit from the backup reservation if their price difference is large enough that $(p_r^{(V)} - p_r^{(R)}) > S_i p_r^{(R)}(1 - \frac{1}{k\beta})/(\frac{b_i}{l^{(V)}} - M_i^{(V)})$, or the competition intensity is low enough that $k < \frac{S_i p_r^{(R)}/\beta}{S_i p_r^{(R)} - (p_r^{(V)} - p_r^{(R)})(b_i/l^{(V)} - M_i^{(V)})}$

Proposition 4 implies that, different from the results under the independent situation, the operators can still benefit from the backup reservation when $p_r^{(V)} < p_r^{(R)}$, as long as $l^{(V)}$ satisfies $l^{(V)} < \frac{l^{(R)} S_i p_r^{(R)}/k}{S_i p_r^{(R)} - (p_r^{(V)} - p_r^{(R)})(b_i/l^{(V)} - M_i^{(V)})}$. And even if $p_r^{(V)} > p_r^{(R)}$, the backup reservation may not necessarily work. Besides, the following result can be obtained.

Lemma 3. With backup reservation, given the service level and uniform demand distribution at the NEO, the resources to be shared under the competitive scenario is not larger than that under the independent scenario.

Stage 1: The NEO sets the service level

Now we analyze the NEO's the optimal value of $l^{(V)}$ or $p_r^{(V)}$, as in (7), but with a different profit function (10). The algorithm for calculating the optimal value of service level is similar to that under the independent scenario. Next, we will rely on numerical analysis to further compare the results in independent and competitive markets.

V. NUMERICAL RESULTS

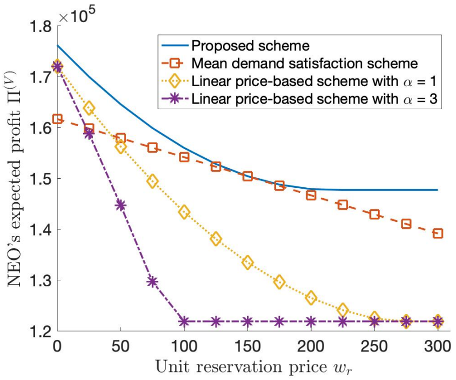
To further investigate the effects of various system parameters on the benefits of NIS through backup reservation, we conduct a thorough numerical study. We consider an example of spectrum sharing between two operators. Channels are modeled as orthogonal, thus relegating the problem of channel interference. We will focus on the basic model with only one service market with uncertain user number following uniform distribution $U(a_0, b_0)$, so we omit the subscript i here, and the base parameter set is provided as: $M^{(V)} = 200$, $M^{(R)} = 600$, $S = 100$, $w = 300$, $p_r^{(R)} = 400$, $P = 100$, $\alpha = 80$, $h = 120$, $n_0 = 50$, $l_{\max}^{(V)} = 10$, $k = 1$, $a_0 = 1500$, $b_0 = 4500$, where the NEO's service price has a nonlinear relationship with its service level as in Section II.

A. *Comparisons with Other Reservation Policies*

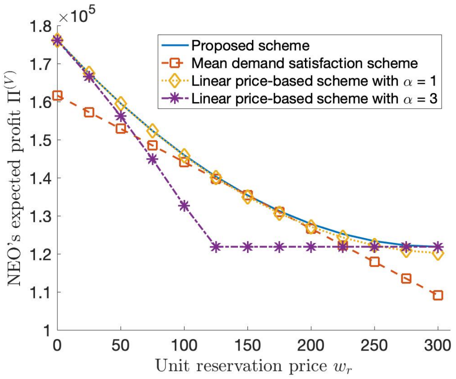
Firstly, we compare our reservation policy with the following two reservation policies: a mean demand satisfaction strategy and a linear price-based strategy. The former one indicates that the reservation quantity is made so that the mean demand can always be satisfied, i.e. $R+M^{(V)}+S \geq \mu$ under independent scenario, or $R + M^{(V)} \geq \mu$ under competitive scenario, regardless of the reservation price. This strategy may be adopted by the operator for its simplicity. In the linear price-based strategy, the reservation quantity is linearly dependent on the reservation price as in $R = D - M^{(V)} - \theta w_r$, where D is the highest possible resource demand (note in independent markets with uniform demand, $D = \frac{b_0}{l^{(V)}} - S$). The ROO would set the reservation price not higher than the value of $p_r^{(V)} - w$. The comparison results for the NEO are shown in Fig. 2 with different values of the reservation price under an arbitrary value of $l^{(V)} = 8.0$, which illustrates clearly the dominance of our reservation policy over the other two policies with respect to the NEO's expected profits, in either independent or competitive markets.

B. *The Effects of Demand Variance*

Denote the profit difference $\Delta\Pi^{(R)} = \Pi_2^{(R)} - \Pi_1^{(R)}$ as the value of backup reservation for the ROO. The results under three levels of demand uncertainty (high ($U(1000, 5000)$), moderate ($U(1500, 4500)$) and low ($U(2000, 4000)$) are: 8981, 7771, 6654 in independent markets and 15313, 14729, 13935 in competitive markets respectively. It is revealed that the ROO is more willing to cooperate through backup reservation under larger demand risks, and benefits from the reservation more under competitive scenario than under independent scenario.



(a) Independent markets



(b) Competitive markets

Fig. 2. The NEO's expected profit under three reservation policies vs. w_r.

C. *The Effects of Redundant Resource Capacity*

To see whether the ROO's potential redundant capacity affects the performance outcomes, we change the value of S from 100 to 300, with the constant value of $M^{(R)} = 600$. Table I reports the results related to the optimal reservation decisions and the corresponding profits, from where three important observations can be made. First, under the independent scenario, both the reservation price and quantity decrease with the ROO's redundant capacity S. This is because there is less need for the NEO to make reservations when there is more redundant capacity available at the ROO. While under the competitive scenario, the impact of S on their reservation decisions are negligible, which implies that, the NEO doesn't actually need to know the redundant capacity of its competitor when making reservation decisions.

Secondly, denote the profit difference $\Delta\Pi = \Pi_2 - \Pi_1$ as the benefit of backup reservation for the two operators, the value of which is always higher under the competitive scenario. $\Delta\Pi$ decreases with S under the independent scenario since less reservation is made, while it increases slightly under the competitive scenario. This is because, larger redundant capacity indicates less need to compromise the ROO's own user demand when the NEO shares the spectrum, thereby increasing the benefit of the backup reservation. Hence, the implementation of a backup reservation scheme is most effective in improving profits for the competitive scenario or the independent scenario with small redundant capacity. Finally, if we use $\Delta l^{(V)} = l_1^{(V)} - l_2^{(V)}$ to denote the improvement in the service level when implementing backup reservation scheme, it can be seen that the end-users benefit more from

TABLE I
EFFECTS OF REDUNDANT CAPACITY ON THE RESERVATION DECISIONS AND THE VALUE OF BACKUP RESERVATION.

S	Independent markets				Competitive markets			
	w_r^*	R^*	$\Delta\Pi$	$\Delta l^{(V)}$	w_r^*	R^*	$\Delta\Pi$	$\Delta l^{(V)}$
100	129	104	12287	0.051	178	144	23347	0.079
200	80	66	4967	0.033	179	144	23579	0.105
300	34	28	1031	0.017	179	145	24317	0.151

TABLE II
EFFECTS OF MARKET COMPETITION ON THE RESERVATION DECISIONS.

S	(Reservation price, Reservation quantity)				
	$k = 0.2$	$k = 0.4$	$k = 0.6$	$k = 0.8$	$k = 1.0$
100	(178,144)	(178,144)	(178,144)	(178,144)	(178,144)
200	(140,185)	(152,173)	(162,162)	(171,152)	(179,144)
300	(75,260)	(108,225)	(135,196)	(158,169)	(179,145)

the reservation-based NIS when the operators compete.

D. The Effects of Market Competition

NIS is supposed to benefit both partners through cost sharing and larger market share. However, previous studies have assumed the independence between the markets of the service providers. Table II illustrates the impacts of competitive intensities on the reservation decisions. When S is small, the impact of competition intensity k is negligible, because the NEO reserves all of its redundant capacity and no new subscribers are expected to switch to the ROO; but when S is large, as the competition intensity increases, the ROO would increase the reservation price to inhibit the reservation and to keep more resources for new subscribers.

As for the value of backup reservation, the value of $\Delta\Pi$ decreases from 42525 to 23347 as the value of k increases from 0.2 to 1.0 when S = 100, and decreases from 81918 to 24317 when S = 300. The decrease rate is higher under large S than that under the counterpart, because the benefit from cooperation is moderated by the ROO's behavior in inhibiting the reservation quantity for more new subscribers.

Moreover, if we use $E\{1 - \frac{unusedspectrum}{totalspectrum}\}$ to represent the spectrum efficiency, the total spectrum efficiency can be calculated as $1 - \frac{\int_0^{M_i^{(V)}+S_i}(M_i^{(V)}-x_i+S_i)f_i(x_i)dx_i}{M_i^{(V)}+M_i^{(R)}}$. For example, the efficiency is 70.8% without backup reservation and increases to 72.0% under reservation with S = 400. We can easily observe that the spectrum efficiency is larger when the backup reservation is used, because the optimal value of $l^{(V)}$ is decreased which results in larger resource demand.

VI. RELATED WORK

In recent years, NIS has emerged as an important research area with interest from both academic researchers and industrial practitioners. Existing literature on sharing models have identified a wide range of factors that determine how network infrastructure are allocated and affect the effectiveness of sharing strategy. Current studies typically focus on examining them in one of the two categories: service market profile and infrastructure market profile. The studies in the former include but are not limited to the service demand pattern, market shares, regulations on the market concentration, interference and traffic cost [17]–[19]. While [20] argues that the market shares of the operators should be taken into consideration to guarantee coalition stability, most models assume fixed market shares or user numbers [20]–[22]. [23] shows the impacts of tight competition regulations on the market concentration, while how the competition among service providers affects their resource sharing decisions has not been investigated. The studies in the later refer to the relationships among the operators which cannot be avoided when multiple operators are considered in resource sharing or trading market. The existing literature normally considers the price competition/cooperation among multiple resource suppliers [22], [24]–[26]. Our study tries to investigate both the competition in services and the coopetition in resource sharing. Moreover, how the factors in both markets, including the uncertain demand risks, the long-term backup contract design, and the potential redundant resource capacity, affect the sharing decision configurations and economic performances is explored in our research.

In determining how the resources or benefits should be allocated among the operators in NIS, one stream of research, mostly in the area of spectrum sharing for unlicensed bands, looks for the sharing rules that lead to fairness and efficiency [27]–[30]. Another stream of research conducts a cooperative game approach [20], [31]. However, challenges that have not been fully addressed still exist in real world NIS, including preserving a liable, mutually beneficial relationship for the operators, reserving an appropriate backup capacity and ensuring supply under uncertain resource demand. To combat these challenges, we generalize and develop the well-structured partnership between partners to ensure supply availability in NIS mechanism under demand uncertainty. Different from many papers in the literature, our interest is in the interactions between the operators participating in both the resource sharing cooperation and the service competition. Through backup contract design and parameter optimization, the operators' effort and willingness to collaborate should increase.

Work on long-term contract design between operators in NIS is limited. There has been some work that relies on different types of contracts to incentivize spectrum sharing, like revenue sharing [32], and insurance contracts [18]. However, the contract parameters are assumed to be exogenous, which determine how the economic benefits are allocated between the partners. Our work tries to optimize the contract parameters for a realistic profit allocation mechanism. [22] obtains the optimal service prices to maximize the cross-carrier MVNO's profit, but how the resource allocation can be implemented through pricing for maximum ISPs' profit are not fully studied. Of particular relevance is the work of [12] on the spectrum reservation contract between a third-party broker and a unlicensed white space device. Our model focuses on the co-opetition relationships between two operators providing similar services to the end-users. An altogether different approach to the spectrum sharing/trading problem is the one taken by the mechanism design literature. There, the primary users offer a direct mechanism that allocates its resources as a function of secondary users' reports of their private information, such as transmission efficiency [13], and preference for a given spectrum quality [33]. Our paper contributes to this literature by applying the theory of backup contract design to the problem of network infrastructure sharing in an uncertain and competitive environment. Our contract-based approach provides a richer form of representing relationships among operators than the previous auction-based approach, and enables us to evaluate the feasibility and effectiveness of cooperation among competing operators.

VII. Conclusions

In this paper, we propose the optimal NIS policies based on the equilibrium of the backup reservation game between two operators. The decision-making conditions are identified for the operators in a game setting to adopt and implement the backup reservation contract for both independent and competitive scenarios. The interactive decisions of the two operators, namely the reservation price and the reserved quantity, are obtained under uncertain demand risks. The strategic backup reservation based infrastructure sharing framework is shown to increase both the capacity utilization of the resource-owning operator and the virtual operator's service level to the end-users. The benefits of such a scheme are determined by various factors such as the demand uncertainty, the potential redundant capacity, and the competitive intensity. The findings provide a clear guideline for the operators to choose their partners and determine their action plans when NIS is desired in volatile and competitive markets. For future research, extending this study to price-sensitive demand will be of interest to assess the generality of the conjectures. It would also be worthwhile to relax the assumption of the availability of complete information among the operators.

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