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The Economics of Multi-Network Access

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***Abstract*—Traditionally, a cell phone remains on a single, primary mobile network operator (MNO) as long as it is available, and roams onto another MNO only when outside the primary MNO's coverage. Multi-network access (MNA) is a new scheme where a cell phone may use any one of multiple MNOs at any place, anytime. One such example is a multi-operator mobile virtual network operator (MO-MVNO) like Google Fi. This paper quantifies how much MNA can reduce the cost of cellular data services, and shows that the amount of infrastructure and/or spectrum resources needed to produce a given network capacity can be reduced by over 20%. Greater resource savings can be realized if MNA-capable devices attach to towers of higher SINR rather than higher expected data rate. The amount of resources saved increases faster than linearly with increasing fraction of MNA-capable devices on the network, so as an MO-MVNO gains market share, it could demand better wholesale prices from partner MNOs. If the distribution of traffic volume between partner MNOs shifts significantly with MNA, an MNO losing traffic share may not have an incentive to participate in MNA unless it could demand a much higher wholesale price than other partner MNOs, possibly close to or even above the retail price net of market cost. The eventual economic impacts on each operator adopting MNA are the result of complex considerations involving not only business decisions like investment and wholesale pricing, but also technical parameters like network selection algorithms and resource allocation schemes.**

***Keywords*—MO-MVNO, cost efficiency, capacity sharing, resource allocation, roaming, Google Fi**

I. Introduction

Traditionally, a cell phone is served by a single primary mobile network operator (MNO), and uses another MNO (roams) only when the primary is unavailable and a roaming agreement exists. More recently, the multi-network access (MNA) model [1] has emerged, where a cell phone may use the infrastructure of any one of multiple MNOs at any point in space and time. One example of MNA is Google Fi, a multi-operator mobile virtual network operator (MO-MVNO) that partners with multiple MNOs (T-Mobile, Sprint and US Cellular in the US). By allowing user equipment (UEs) to be served by a larger set of distinctively located base stations (BS's), MNA improves the spectral efficiency of wireless networks [1]. It has been shown that MNA can increase network capacity by as much as 80% without additional spectrum or infrastructure. As the world moves to build networks that can accommodate the ever-increasing demand for mobile data, adopting MNA can reduce the resources needed to achieve that goal, lower cost and increase social welfare. This paper examines the economics of MNA in the context of an MO-MVNO.

We are first concerned with how much MNA can reduce the cost of cellular data services. Tower infrastructure and spectrum licenses account for significant expenses for facility-based MNOs, but fewer of these resources are needed to produce a given capacity if MNA is adopted, thanks to its higher spectral efficiency. With MNA, the total network capacity depends on many factors, including the fraction of UEs that are capable of MNA, the relative tower density and spectrum bandwidth between partner MNOs, the network selection algorithm employed by MNA-capable UEs, and MNOs' resource allocation schemes. We will examine the cost efficiency of MNA-enabled cellular networks in a variety of scenarios along these dimensions. We will then determine how the cost savings can translate into lower prices for consumers and/or higher profits for operators.

Besides Google Fi, the adoption of MNA has been quite limited to the best of our knowledge, which prompts a question about incentives. Under what conditions are MNOs willing to partner with an MO-MVNO? Given the potential cost savings, when would an MNO offer wholesale discounts, and by how much? Building upon the cost analyses, we also seek to characterize the business arrangements that allow both MNOs and MO-MVNOs to benefit from MNA. From an MNO's perspective, partnering with an MO-MVNO can be a double-edged sword. On one hand, MNOs may save costs and gain wholesale revenue, some of which may come from previous subscribers of a competing MNO. On the other hand, an MNO's retail revenue may diminish as some subscribers switch to an MO-MVNO. Unless the net effect is positive on the bottom line, an MNO is unlikely to adopt MNA. From an MO-MVNO's perspective, it also needs to be profitable to stay in business, which creates another constraint on the range of wholesale prices that would make MNA attractive for all operators involved. As we will demonstrate, an MNA arrangement should factor into not only business decisions, like how much each MNO invests in infrastructure and spectrum resources, but also technical parameters, like resource allocation schemes and network selection algorithms. We will discuss how these aspects influence the range of wholesale prices that can incentivize MNOs and MO-MVNOs alike to adopt MNA. We will identify

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realistic scenarios where wholesale prices may appear unusual, and yet still benefit all stakeholders.

The rest of the paper is structured as follows. Section II discusses related works. Section III describes our method, key assumptions, and simulation and economic models. We present the results in Section IV and conclude in Section V.

II. Related works

A. Overview

The possibility of first responders roaming to multiple MNOs was discussed in [2], [3]. The potential for greater total capacity when UEs connect to the BS with the strongest signal regardless of its provider was discussed in [4]–[6]. Few works have investigated the cost savings as a result of MNA and how the saving is related to parameters like network selection algorithms and operators' market share, although related issues have been explored. Some examined the effect of MNA on capacity without cost analyses [7]–[12]. Others addressed the dynamics between an MVNO and MNOs either in a traditional context without MNA [13], or in the MNA context but without considering the efficiency improvements from MNA [14].

Another category of related works is concerned with improving a UE's network selection algorithm. Most are designed in the context of Heterogeneous Networks (HetNets), improving the logic of switching between cellular and Wi-Fi. Only a few studies are conducted for UEs that can freely access multiple cellular networks. Our paper considers different selection algorithms and highlight their efficiency implications in the context of MNA, although we do not attempt to optimize the algorithm for a specific objective.

B. Performance Implications of Multi-Network Access

MNA's effects on capacity and how they relate to MO-MVNO market share, resource allocation schemes and network selection algorithms are investigated in [1] for the case of similarly sized partner MNOs. Our work complements [1] by measuring how the spectral efficiency gains translate into better profitability for network operators, and/or lower prices for consumers. We further discuss how the economic outcomes and incentives to adopt MNA may differ for partner MNOs that own different amounts of tower and spectrum resources.

Many of the previous works on the performance implications of MNA use the stochastic geometry model proposed by [15], which assumed that UEs connect to the nearest BS. They did not explore alternative network selection algorithms as in this paper, such as algorithms that consider not only distance but also SINR and expected data rate.

Reference [7] examined MNA in the form of subscribers having cell phone plans from multiple MNOs. An urban hot zone (e.g. a train station) was simulated where each user reevaluates available BS's every one second and attaches to the one that provides higher expected data rate. In the case of 2-MNO MNA, the paper found an improvement in the mean UE data rate on the order of 15% when all UEs are MNA-capable, which is smaller than our results, likely due to different BS layouts. Economic implications were not explored. We studied a network of greater scale (16 BS's per MNO compared to 4). We also considered alternative network selection algorithms and resource allocation scheme, scenarios where MNA-capable UEs are in between 0 and 100% of all UEs, and scenarios where MNOs have unbalanced tower and spectrum resources.

Reference [10] compared the performance of capacity sharing, spectrum sharing and sharing on virtualized infrastructure. Capacity sharing was shown to perform better than spectrum sharing. Virtualized physical resource block sharing and virtualized spectrum sharing can achieve similar performance to that of capacity sharing, but are more complex and costly to implement. The author did not consider alternate network selection algorithms – UEs were assumed to attach to the BS that gives the highest signal power. The potential for lower infrastructure cost was not explored.

References [11], [12] quantified the performance benefit of MNA as a function of the offset in tower locations and sector orientation using a hexagonal grid model. MNA was found useful even with tower colocation if sectors are not fully aligned. The authors assumed all UEs were MNA-capable, and did not consider alternate resource allocation schemes or scenarios where MNOs have different tower densities. The economic impact of MNA was not explored.

C. Network Selection Algorithms

The question of how to choose among multiple BS's arises in the context of the radio access technology (RAT) selection problem in heterogeneous networks and is treated in [16]–[22]. The objectives of the proposed algorithms vary, e.g. to maximize throughput, fairness or some measure of utility. The typical scenario of RAT selection problems is a UE attempting to optimize selection of a network interface, usually between Wi-Fi and cellular. Our work applies to the selection of cellular carriers regardless of whether they use the same RAT. Only a few works are available in this context. Reference [23] identified the deficiencies in the built-in network selection algorithm of Google Fi, and designed solutions that improve throughput and switching latency. Our paper builds on this research to explore a range of selection algorithms, and how they affect the cost efficiency of cellular networks that support MNA.

D. Interactions between MNOs and MVNOs

Reference [14] discussed the partnering strategy and optimal pricing in a market with two MNOs and one MVNO. Using a Stackelberg game theoretic model, the authors derived profit-maximizing wholesale and retail pricing, and characterized the conditions for which both MNOs choosing to partner with the MVNO is the unique Nash equilibrium. The potential spectral efficiency gain as a result of partnering with more than one MNOs were not explored. The additional profits to be shared among operators were the result of the MVNO's assumed ability to offload traffic to free Wi-Fi hotspots and to earn side revenue (e.g. ads) from its customers. Our work quantifies the potential efficiency gain from such an arrangement and how to divide up the cost savings in a way that benefit all stakeholders.

Reference [24], [25] explored the pricing strategy and profitability of an MO-MVNO. The MO-MVNO was assumed to offer a pricing structure that attracted low usage consumers and had access to free Wi-Fi hotspots whereas the MNOs did not. It was concluded that an MO-MVNO was only viable in the short term, as consumers' monthly data consumption would increase in the long run. While [24] showed improvements in UE data rate, the effect of MNA was not isolated from the effect of additional Wi-Fi hotspots. The implications on cost were not considered. Neither were the effects of the resource allocation scheme and network selection algorithm.

III. Method and Model Assumptions

This section presents our method, key assumptions made and how they might have influenced our results, and the simulation and engineering economic models.

To determine how many tower and spectrum resources can be saved by adopting MNA, we built a MATLAB simulator that computes the amount of resources needed to produce a given downlink capacity with MNA and without MNA, for a preset distribution of tower and UE locations. The outputs of the simulator feed into an engineering economic model that calculates an operator's revenue and costs. We determine if an operator has the incentive to adopt MNA by comparing the operator's profit with MNA against that without MNA. We focused on the MO-MVNO form of MNA, and looked at an MO-MVNO that partners with two MNOs.

Section III.A discusses the characteristics of the towers and users, the propagation model and how we determined network capacity. Section III.B explains our choice of simulation parameters and describes MNOs' resource allocation schemes and the network selection algorithms used by MO-MVNO subscribers. Section III.C introduces the engineering economic model that underlies our revenue and cost analyses. We derive the range of acceptable wholesale prices for each operator to have an incentive to adopt MNA in Section III.D. Section III.E explains the baseline values chosen for a numerical evaluation of operators' economic outcomes.

A. Key Assumptions

We assume that UEs are stationary and uniformly distributed throughput the simulated area. We also assume a full-buffer traffic model, i.e. UEs always have data to receive from BS's.

We assume that towers are uniformly distributed throughout the simulated area. We choose this assumption because it allows us to easily examine situations in which partner MNOs have different tower densities, and because it naturally includes cells of various shapes and sizes. These advantages are balanced by a weakness: because tower locations are generated independently of UE locations, there will be areas with many UEs and no towers nearby, and areas with towers but very few UEs to serve. There can be instances where two towers belonging to different MNOs are closely positioned, although we do not explicitly model colocation.

We assume each BS transmits at a fixed power P_t across the available bandwidth B. The received power P_r at distance d is calculated by (1), where α is the path loss exponent, G_t and G_r are the transmitter and receiver antenna gains, respectively, and λ is the wavelength at the transmission frequency. Our model does not consider fading.

$$P_r(d) = P_t G_t G_r \frac{\lambda^2}{(4\pi)^2 d^\alpha} \quad (1)$$

We assume that the downlink data rate approaches the Shannon limit. The data rate r_j in bits per second for UE j at distance d from the BS is $r_j(\mathrm{d}) = s_j B \log_2\left(1 + \frac{s_j P_r^j(\mathrm{d})}{s_j I^j + s_j B N_0}\right)$ or

$$r_j(\mathrm{d}) = s_j B \log_2\left(1 + \frac{P_r^j(\mathrm{d})}{I^j + B N_0}\right) \quad (2)$$

Here, s_j is the share of spectrum resources assigned to UE j in its cell; P_r^j is the received signal power at UE j across available bandwidth B; I^j is the sum of interference power across B from all other co-channel BS's, where we have assumed a frequency reuse factor of 1. We assumed a fixed noise power spectral density N_0.

In comparing the economic outcomes of all operators before and after they participate in an MNA arrangement with an MO-MVNO, we assume that the MNOs' combined network capacity is the same with MNA as it is without MNA. We also assume that the total number of customers is the same with or without MNA. Given that total capacity, total number of users and expected user data rate are the same with and without MNA, we can reasonably assume that the retail price for mobile data service is also the same with or without MNA. In other words, the total revenue opportunity is the same with or without MNA. This allows us to compute the change in an operator's profitability independent of a specific (and potentially inaccurate) demand function and price elasticity. Another way to look at it is that we are modeling MNA as an option for operators to meet a future capacity requirement which is exogenously given, rather than a way to extract more capacity from existing tower and spectrum resources.

For a given communications standard (e.g. LTE), network capacity depends primarily on tower density and the available spectrum bandwidth. With increased spectral efficiency, an MNO can carry the same traffic with less infrastructure, less spectrum or less of both. In computing potential cost savings, we assume that MNOs adjust tower density and spectrum bandwidth in tandem, as a cost-minimizing MNO would do [26] when cost per tower and cost per MHz of spectrum are fixed.

While not explicitly considered in our model, there are other costs associated with bringing MNA to fruition. For example, devices that support more spectrum bands and communications standards in order to take advantage of MNA might be more expensive than those that do not. There might be a cost on the network side if the base station scheduler software in existing infrastructure needs to be updated to maintain certain fairness objectives under MNA, as we will discuss later. There is also a transaction cost in developing an MNA agreement that satisfies all stakeholders, be it an MVNO wholesale agreement or a capacity sharing agreement. We assume these costs are insignificant relative to infrastructure and spectrum expenses.

B. Simulation Model

We simulated an area of approximately 7 km by 6 km that is wrapped around at all four edges, creating effectively a torus. In the case where both partner MNOs have the same amount of tower and spectrum resources, each MNO has 16 towers and 60 MHz of spectrum bandwidth, of which 30 MHz is for downlink. If the 16 towers were distributed on a hexagonal grid in this area, each cell would have a radius of roughly 1 km. The amount of tower and spectrum resources are adjusted in proportion when we investigate scenarios in which partner MNOs have unequal capacities.

Transmit power P_t is 40 Watts or 46 dBm. The path loss exponent choice of $\alpha = 3$ accounts for both the effects of clutter and long-term fading; short-term fading is not likely to significantly affect the long-term average data rates we present here. Noise power spectral density $N_0 = -174$ dBm/Hz. Transmit antenna gain after cable loss $G_t = 14$ dBi. Receiver antenna gain $G_r = 0$ dBi. Wavelength $\lambda = 0.429$ meters, corresponding to 700 MHz frequency.

We assume that there are 3200 active UEs in total across the two partner MNOs and the one MO-MVNO. We vary the fraction of UEs that are subscribers of the MO-MVNO, while the remaining UEs are assumed to be split between the partner MNOs in proportion to the MNOs' capacities.

The share of spectrum resources UE j is allocated in its cell, s_j, is given by (3):

$$s_j = \beta[\log(1 + SINR_i)]^{\gamma} \tag{3}$$

Here, β is a constant and γ is a parameter that controls the tradeoff between throughput fairness and total throughput. The larger γ, the more high-SINR UEs are favored (though cell edge UEs may be starved), which increases total capacity. The smaller γ, the more low-SINR UEs are favored, which reduces the difference in data rate between UEs, thereby increasing throughput fairness. We name three special cases, which span a wide range in terms of the tradeoff between throughput fairness and total throughput:

- "Equal-Allocation": $\gamma = 0$. All UEs in a cell receive an equal fraction of spectrum resources. As a result, each UE's throughput can be drastically different due to their varying distances to the tower, though total throughput is higher.
- "Equal-Throughput": $\gamma = -1$. Each UE in a cell receives a fraction of spectrum resources such that all UEs in the cell get the same throughput.
- "Balanced": $\gamma = -0.5$. This compromise scheme should most closely resemble real world MNO practices.

Moreover, when a cell contains subscribers of both an MNO and an MO-MVNO, an additional adjustment may be made by tuning resource allocation coefficient β to reduce the disparity in mean data rate of MNO and MO-MVNO subscribers. Without such an adjustment, MO-MVNO subscribers would receive higher data rate on average than MNO subscribers for being closer to a tower on average.

We examined the following two network selection algorithms to be used by MO-MVNO subscribers.

- "Maximum-SINR": An MO-MVNO UE will attach to (the MNO of) the BS that provides the highest SINR.
- "Maximum-Throughput": An MO-MVNO UE will first find BS with the highest-SINR belonging to each MNO, and then attach to the one that provides higher expected throughput. We assume that the UE knows precisely the data rate it would receive, as if it were able to test and observe the performance on each MNO BS.

C. *Engineering Economic Model*

We assume that an operator's retail and wholesale revenues are proportional to the retail and wholesale traffic volumes it carries, respectively. Total revenue for MNO i ($i = \{A, Z\}$) R_{ik} is given by (4), where p^r is the retail revenue per unit of traffic, and p_{ik}^w is the wholesale price per unit of traffic MNO i charges. Subscript k denotes whether MNA is adopted. $k = 0$ if MNA is not adopted. $k = 1$ if MNA is adopted.

$$R_{ik} = p^r v_{ik}^r + p_{ik}^w v_{ik}^w \tag{4}$$

This resembles the pricing model of today's operators, which usually charge more for a higher data quota. While many operators also sell "unlimited" plans, most of them include a hidden data consumption threshold beyond which a subscriber's peak data rate will be significantly throttled. There may be intangible benefits from having a direct relationship with end users that are not necessarily reflected in the revenue from selling cellular data, like better ad targeting. Such benefits are not explicitly considered in our model.

We assume that an MNO's cost for spectrum C_{ik}^S is proportional to its spectrum holdings bandwidth B_{ik}, and that all MNOs face the same cost per unit of spectrum per unit of time per unit of area k^S $\left(\frac{\$}{km^2 \cdot Hz \cdot Sec}\right)$.

$$C_{ik}^S = k^S B_{ik} A \tag{5}$$

Since spectrum licenses are routinely renewed at a minimal cost, they are considered "indefinite-lived" assets [27]. We calculate the cost of spectrum as the interest paid on the initial capital expenditure to acquire the spectrum as follows, where $p_{auction}$ is the price per MHz-Pop , ρ is population density ($\#/km^2$), and d is the interest rate or cost of capital:

$$k^S = p_{auction} \rho d \tag{6}$$

Operators also incur a cost to perform marketing, customer support, billing and other retail functions (hereinafter referred to as simply "marketing cost"). We assume that a fixed share k^M of *retail* revenue is used to perform marketing.

$$C_{ik}^M = k^M p^r v_{ik}^r \tag{7}$$

Tower cost is proportional to the number of towers, with coefficient k^T. A portion of the tower cost may depend on the capacity per tower or the spectrum bandwidth available at each tower. We assume that any such variation is insignificant compared to overall tower costs.

$$C_{ik}^T = k^T t_{ik} \tag{8}$$

Let $p^{rnm} = p^r - k^M$. For MNO i: Profit = retail revenue + wholesale revenue – spectrum costs – tower costs – marketing costs.

$$\pi_{ik} = p^{rnm} v_{ik}^r + p_{ik}^w v_{ik}^w - k^S B_{ik} A - k^T t_{ik} \tag{9}$$

The profit for the MO-MVNO:

$$\pi_{MO-MVNO,k} = \sum_{i=A,Z} v_{ik}^w (p^{rnm} - p_{ik}^w) \tag{10}$$

TABLE I. SUMMARY OF VARIABLES

i	MNO index
j	UE index
k	$k = 0$ indicates MNA is not adopted. $k = 1$ indicates MNA is adopted.
v_{ik}	Total traffic volume of MNO i ($bits$)
v_{ik}^r	Retail traffic volume of MNO i ($bits$)
v_{ik}^w	Wholesale traffic volume of MNO i ($bits$)
A	Area of coverage, same for all MNOs (km^2)
B_{ik}	Spectrum holdings of MNO i (Hz)
t_{ik}	Number of towers of MNO i in the area A
k^T	Constant for tower cost ($\frac{\$}{tower \cdot sec}$)
k^S	Constant for spectrum cost ($\frac{\$}{Hz \cdot sec \cdot km^2}$)
k^M	Share of retail revenue used for marketing and other retail operating expenses
p^r	Price per unit of retail traffic carried ($\frac{\$}{bit}$)
p_{ik}^w	Price per unit of wholesale traffic carried ($\frac{\$}{bit}$)

A summary of variables is provided in Table I.

D. *Feasible Wholesale Prices*

We assume that MNOs would only partner with an MO-MVNO if they could earn more profits, and that an MO-MVNO must earn positive profits to remain in business. A pair of partner MNO wholesale prices is considered feasible if the following two conditions are satisfied:

1. Both partner MNOs earn more profits if they partner with the MO-MVNO than if they do not.
2. The MO-MVNO is profitable.

Condition #1 yields the lower bound of feasible wholesale prices. Setting $\pi_{ik} \geq \pi_{i0}$ yields:

$$p_{ik}^w \geq p^{rnm} \frac{v_{i0}^r - v_{ik}^r}{v_{ik}^w} - \frac{k^S(B_{i0} - B_{ik})A + k^T(t_{i0} - t_{ik})}{v_{ik}^w} \quad (11)$$

The right-hand side of (11) is a function of an operator's retail and wholesale traffic volumes with and without MNA, and the tower and spectrum resources it deploys with and without MNA. As our results will show, MNA can change how traffic volume and the associated revenue are distributed between partner MNOs, depending on the relative amounts of tower and spectrum resource as well as choices among resource allocation schemes and network selection algorithms. These parameters need to be considered for an MNA agreement, because they can influence whether and how much one partner MNO gains or loses revenue, and the extent to which that partner MNO can save on costs.

Solving Condition #2 yields the upper bound of feasible wholesale prices. Set $\pi_{MO-MVNO,k} > 0$ yields:

$$p_{Ak}^w < -\frac{v_{Zk}^w}{v_{Ak}^w} p_{Zk}^w + p^{rnm}\left(1 + \frac{v_{Zk}^w}{v_{Ak}^w}\right) \quad (12)$$

We define a *feasible region* to be the collection of feasible wholesale prices for a given distribution of traffic volume and resource investment between partner MNOs.

E. *Parameters for Numerical Evaluateion*

To calculate the amount of traffic carried, we assume that the throughput at the peak hour is 80% of the total network capacity and that the throughput averaged over the busy hour is five times the throughput averaged over all hours [28]. Revenue per unit of time from data traffic is then capacity*(peak usage rate)/(peak to average ratio)*(price per unit of traffic). We set retail market price $p^r = \$10/GB$ based on current Google Fi pricing [29].

We set spectrum price at $\frac{\$2}{MHz*Pop}$, based on recent results from FCC auctions on low-band spectrum [30]. Population density is set at $\frac{2000\ Pop}{km^2}$, similar to that of a medium-sized city like Pittsburgh. We use a discount rate of 7%. Under these assumptions, the spectrum cost coefficient $k^S = \frac{\$2}{MHz*Pop} * \frac{2000\ Pop}{km^2} * 7\% = \frac{\$280}{MHz*km^2*Year}$.

We use the following estimates for the major components of infrastructure cost. Land lease, amortization of the tower construction, maintenance and utility for a tower site are estimated to cost \$6000 per month, based on the average rent of a tower company and the average number of tenants per site [31]. Base station electronics per cell site with 3 sectors are estimated to cost about \$1600 per month, based on \$100,000 purchase price [32], 5-year useful life and \$0 salvage value. Backhaul is estimated to cost \$3000 per month per cell site with 3 sectors, based on the per-customer revenue of fiber infrastructure companies [31], [33]. Lastly, we assume an additional 10% markup on RAN and backhaul costs to account for upgrading and maintaining the core network [34]. Since our model uses omnidirectional antennae, we divide these costs by 3 to get infrastructure cost per cell in our model.

Finally, we set marketing cost coefficient $k^M = 45\%$ based on T-Mobile's recent income statement, where selling, general and administrative expenses have consistently been about 45% of retail revenue during 2016-2018.

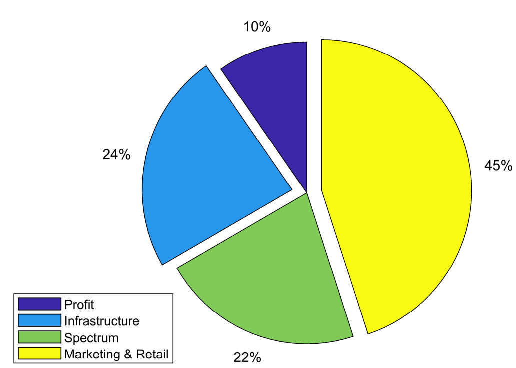

Fig. 1. Breakdown of an MNO's costs and profits without MNA. (16 towers; 60 MHz spectrum; "Balanced" resource allocation.)

Under these assumptions, the breakdown of the costs and profits for an MNO with 16 towers and 60 MHz of spectrum without MNA is shown in Fig. 1.

IV. RESULTS

This section presents our main results. Section IV.A quantifies how much MNA can reduce the cost to provide cellular data services, and how the cost savings vary with various technical parameters. We characterize the wholesale prices that would make all operators willing to participate in MNA in Section IV.B. Section IV.C describes the implications of MNA on consumer welfare and operators' profitability.

A. Reducing Cost of Cellular Data Services

If the fraction of MNA-capable UEs is high, such as when MNOs share capacity directly with each other (referred to by some as "flexible roaming" [8] or "smart roaming" [12]), the same network capacity can be realized with significantly fewer tower and spectrum resources. Fig. 2 shows the fraction of tower and spectrum resources saved as a function of this fraction, which also equals MO-MVNO market share. At baseline, when all UEs are MNA-capable and given a resource allocation scheme that balances total capacity and throughput fairness, 22% of resources can be saved if MNA-capable UEs attach to towers of higher SINR, or 17% if choosing towers of higher expected data rate.

MNA has economies of scale in the fraction of MNA-capable UEs. As shown in Fig. 2, the amount of resources saved increases with the fraction of MNA-capable UEs faster than linearly. With retail prices held constant, the combined profit of the MO-MVNO and MNOs increases faster than linearly as well. Thus, as an MO-MVNO gains market share, it can demand lower wholesale prices, or MNOs are more incentivized to work with MVNOs, or both.

The network selection algorithm employed by MNA-capable UEs plays a significant role in determining the cost-efficiency of MNA networks. MNA is more cost-effective (as measured in tower and spectrum cost per bit of traffic carried) when MNA-capable UEs attach to towers of higher SINR rather than higher expected data rate, because Shannon's theorem predicts a higher spectrum efficiency for a channel with higher SINR. Fig. 2 shows that this difference is large at baseline. Most notably, when only a small fraction of UEs are MNA-capable (e.g. 10%), the selection algorithm makes a huge difference. There are still tangible resource savings if UEs attach to towers of higher SINR. However, if they attach to towers of higher expected data rate, there would be negligible resource savings. From a business perspective, an MVNO such as Google Fi could make the case to its partner MNOs for why they should receive a discount on wholesale rates if their subscribers instead attach to towers of higher SINR, as that makes the MNO networks more efficient.

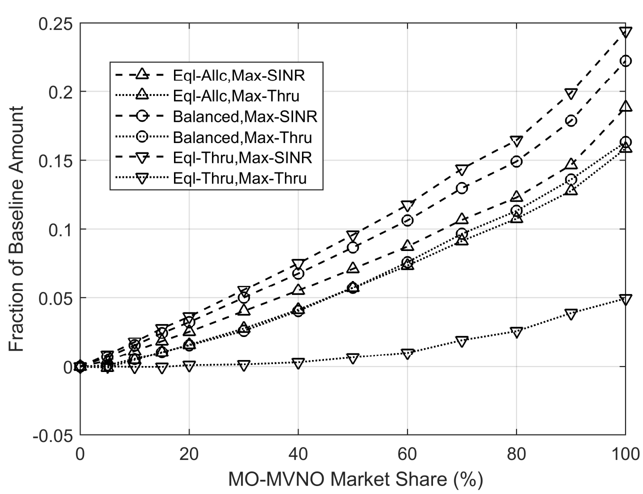

Fig. 2. Tower and spectrum resources saved with MNA (as a fraction of baseline amounts)

The difference in cost-efficiency between the two selection algorithms is larger when MNO resource allocation prioritizes throughput fairness, and is smaller when MNO resources allocation prioritizes total capacity.

B. Feasible Wholesale Prices

The fact that MNA reduces the aggregate investment on tower and spectrum resources that produces a given network capacity does not guarantee the willingness of an individual operator to participate in MNA. Partner MNOs require wholesale prices high enough so that they can benefit from partnering with an MO-MVNO, and the MO-MVNO requires wholesale prices low enough so that it, too, can profit. While the exact prices that all operators agree on are the result of negotiations, we can find the range of wholesale prices that would incentivize each operator to participate in MNA. In this section, we discuss the lower and upper bounds of feasible wholesale prices, and how these prices are influenced by the relative amount of tower and spectrum resources between partner MNOs, the share of traffic carried by each partner MNO and the network selection algorithm used by MNA-capable UEs.

If the traffic share between MNOs does not change with MNA, both partner MNOs will be willing to accept a wholesale price below the retail price net of marketing cost. Assuming that the total traffic volume carried with MNA is the same as that without MNA, when an MNO carries the same share of traffic with MNA as it does without MNA, we have $v_{ik}^w + v_{ik}^r = v_{i0}^r$. The minimum feasible wholesale price (11) can then be simplified to:

$$p_{ik}^w \geq p_0^{rnm} - \frac{k^S(B_{i0} - B_{ik})A + k^T(t_{i0} - t_{ik})}{v_{ik}^w}$$

That is, absent any change in revenue, as long as a partner MNO can produce the same capacity with fewer tower and spectrum resources with MNA as it does without MNA (i.e. $B_{i0} > B_{ik}$ and $t_{i0} > t_{ik}$), that MNO should be able to offer the MO-MVNO a discount off of the retail price net of marketing cost and still make the same profits as it would without MNA.

There are realistic scenarios where traffic share does not change with MNA. One example is when partner MNOs have comparable tower density and spectrum bandwidth between them with or without MNA, absent any mechanism that purposely steers more traffic onto one MNO or the other. The solid triangle in Fig. 3 shows the range of feasible wholesale prices for the scenario where an MO-MVNO partners with two

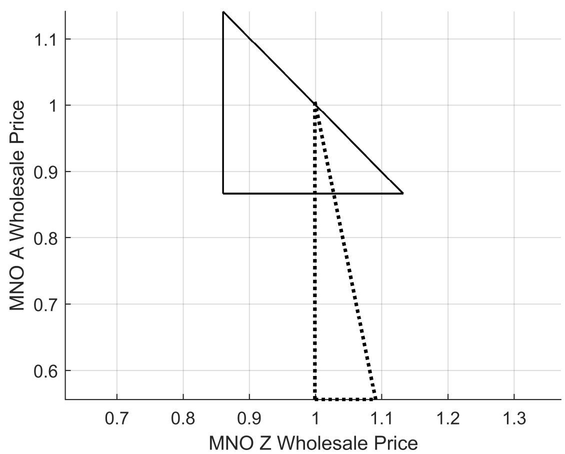

Fig. 3. Feasible wholesale prices. Price is shown as a fraction of the retail price net of marketing cost per unit of traffic. Triangle with solid edges: when the two partner MNOs have equal tower density and equal spectrum bandwidth. Triangle with dotted edges: when one partner MNO has 3x the tower density and 3x the spectrum bandwidth of the other partner MNO. (Balanced resource allocation; Maximum-Throughput network selection algorithm;100% MO-MVNO market share.)

MNOs that have equal tower density and spectrum bandwidth, with all UEs being MNA-capable, under the numerical assumptions in Section III.E. Here, price is expressed as a fraction of the retail price net of marketing cost per unit of traffic. The minimum feasible wholesale price would be lower if tower and spectrum costs represents a higher fraction of revenue. Under our baseline retail price and cost assumptions, infrastructure and spectrum costs represent 45% of revenue (Fig. 1). In this case, both partner MNOs require only 85% of the retail price net of marketing cost (the lower left corner of the triangle) per unit of traffic from the MO-MVNO in order to maintain the same profit with MNA as that without MNA.

If the traffic share between MNOs does change with MNA, the MNO gaining traffic share will be willing to accept a wholesale price below the retail price net of marketing cost, but the one losing traffic share might demand a higher wholesale price, possibly close to or even above the retail price net of marketing cost in order to participate in MNA. This happens when a partner MNO loses so much traffic share with MNA that the savings on tower and spectrum costs are comparable to or even less than its lost retail revenue. Nevertheless, MNA can still benefit all operators in this case.

A significant change in traffic share can happen under realistic conditions. For example, partner MNOs may maintain a fixed division of investments on tower and spectrum resources with or without MNA. If that division is lopsided, traffic share could change considerably and that affects minimum feasible wholesale prices. Given that the relative tower density and spectrum bandwidth between partner MNOs with MNA is the same as that without MNA, if MNA-capable UEs attach to towers of higher expected data rate, the partner MNO with higher tower density and more spectrum bandwidth may carry a *smaller* share of all traffic with MNA than it does without MNA; if MNA-capable UEs instead attach to towers of higher SINR, the partner MNO with higher tower density and more spectrum bandwidth may carry a *larger* share of all traffic with MNA than it does without MNA.

The dotted triangle in Fig. 3 shows the range of feasible wholesale prices corresponding to a scenario where one partner MNO has three times the tower density and three times the spectrum bandwidth of the other partner MNO both with and without MNA, under the numerical assumptions in Section III.E. It was assumed that all UEs are MNA-capable and they attach to towers of higher expected data rate. The MNO with more resources in this example must charge almost the retail price net of marketing cost to maintain the same profit as it would earn without MNA. Even if a partner MNO needs to charge a wholesale price higher than the retail price net of marketing cost, for example, when infrastructure and spectrum costs are relatively small compared to other costs, that does not mean such a wholesale price renders MNA undesirable – all three operators are still better off with MNA than without MNA – but in this scenario the wholesale prices that can distribute the cost savings in a way that benefits all three operators may look somewhat unusual.

There is no realistic scenario where neither MNO could offer a wholesale price that is lower than the retail price net of marketing cost. We prove this by contradiction. Assume, to the contrary, that both partner MNOs charge a wholesale price equal to or higher than the retail price net of marketing cost *and* make the same profits as they do without MNA. The total profits made between partner MNOs are equal to (retail price – marketing cost per unit of traffic)*(total retail traffic) + (wholesale price 1)*(wholesale traffic 1) + (wholesale price 2)*(wholesale traffic 2) – (total tower + spectrum cost). We have shown that MNA always reduces the amount of tower and spectrum resources needed to achieve a given capacity, so total tower + spectrum cost must decrease. We have also assumed that total retail traffic + wholesale traffic 1 + wholesale traffic 2 remain the same. Therefore, if both partner MNOs charge a wholesale price equal to or higher than the retail price net of marketing cost, the MNOs must have made higher profits collectively. That means at least one partner MNO makes more profit than it would without MNA, which contradicts the initial assumption.

An MO-MVNO is more sensitive to the wholesale price charged by one MNO than to that of the other when its traffic is distributed unequally between partner MNOs. In the case of two partner MNOs, as shown in Fig. 3, the line on which the MO-MVNO makes zero profit makes up the hypotenuse of the feasible region. The slope of the hypotenuse is equal to the negative ratio of the traffic volumes carried by the two partner MNOs (12). If the MNO carrying more traffic raises its wholesale price by one unit, for the MO-MVNO to maintain the same profit the MNO carrying less traffic must lower its wholesale price by more than one unit.

C. *Consumer Welfare and Operator Profitability*

As MNA reduces the investment needed on infrastructure and spectrum resources to provide a given capacity, consumers could enjoy lower prices, operators could make more profits, or both. In this section, we discuss the potential impact of MNA on consumers, MO-MVNOs and partner MNOs by examining how an operator's profit could change if it were able to drive a hard bargain and capture all the cost savings from MNA, and how the

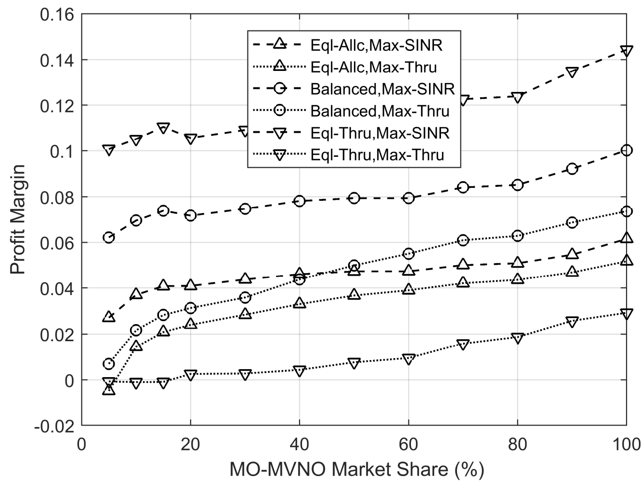

Fig. 4. Potential MO-MVNO profit margin if MNOs passed all cost savings on to it. (MNOs have equal tower density and spectrum bandwidth)

retail price could change if operators pass all the cost savings on to consumers.

When partner MNOs charge their respective minimum feasible wholesale prices, the MO-MVNO can enjoy a healthy profit margin regardless of its market share, provided that it uses an appropriate network selection algorithm. As shown in Fig. 4, when MO-MVNO subscribers attach to towers of higher SINR, the best-case profit margin for the MO-MVNO starts at a decent 6% at low market share and increases gradually to 10% as its market share increases, given "Balanced" resource allocation and the numerical assumptions in III.E. Because the amount of resources saved from MNA is largely commensurate with the fraction of MNA-capable UEs, as we saw in Fig. 2, the profit margin, which measures the ratio of the value of the resources saved to revenue, does not vary with MO-MVNO market share as quickly as the amount of resources saved does.

Even if an MO-MVNO is unable to secure favorable wholesale prices, it can still be a viable business in terms of return-on-investment (ROI), and remain an additional choice of

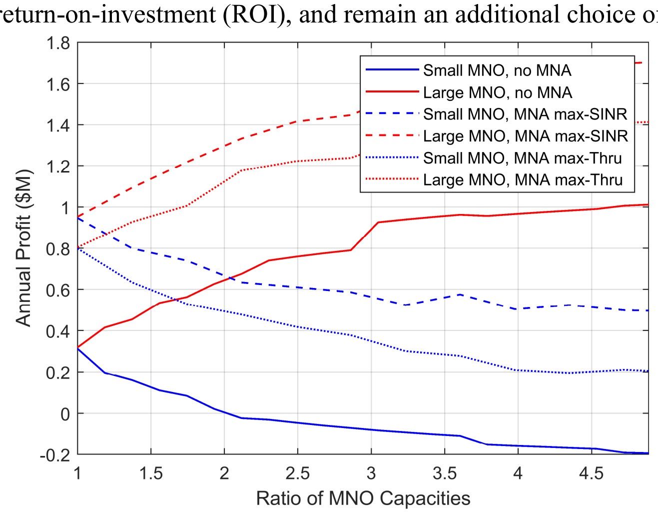

Fig. 5. Best-case MNO profit vs. MNO capacity ratio. (Balanced resource allocation; all UEs are MNA-capable; each MNO carries the same traffic volume with MNA as it does without MNA.)

service providers for consumers. While a profit margin of 10% seems nothing out of the ordinary, the capital investment required for an MVNO is typically much lower than facilities-based MNOs. Therefore, cost savings that are otherwise minor for an MNO generate a sizable ROI for an MVNO which requires fewer assets to operate. Even if its market share is low, or if it is unable to obtain the most generous wholesale prices, an MO-MVNO should still be encouraged to enter the market.

MNA could bring meaningful reduction in the price of cellular data services if operators pass the cost savings on to consumers. At baseline, consumers could see a retail price reduction between 3% and 14% when all UEs are MNA-capable, as a result of resource savings that vary from 5% to 24% depending on the resource allocation scheme and network selection algorithm. The more expensive tower and spectrum are relative to other costs, the more MNA can lower the prices faced by consumers, increase operators' profits, or both.

For partner MNOs, MNA can be an opportunity for tremendous profit growth. Fig. 5 shows each MNO's profit without MNA, and their maximum possible profit with MNA (if that MNO were to capture all the cost savings) for partner MNOs of various sizes. At baseline, for MNOs that both have 16 towers and 60 MHz of spectrum, each makes an annual profit of $0.3 million without MNA. When all UEs are MNA-capable, either MNO can see annual profit increase to $0.8 million if UEs attach to towers of higher expected data rate, or $0.95 million if UEs instead attach to towers of higher SINR.

MNA could have a relatively greater impact on a smaller MNO (lower tower density and lower spectrum bandwidth) than it does for an MNO of larger scale. Absent any change to the combined traffic volume carried between partner MNOs, the maximum possible additional profit is the same for all partner MNOs and is equal to the saved investments in aggregate tower and spectrum resources as a result of MNA. But those same additional profits are more consequential for an MNO with smaller profit margins without MNA. As shown in Fig. 5, due to cellular economies of scale [26], an MNO with higher tower density and higher spectrum bandwidth is more profitable than an MNO with lower tower density and lower spectrum bandwidth. While MNA could bring a healthy uplift in profits for either MNO, the cost savings from MNA would be more significant for the relatively smaller MNO, or even turn around an MNO that is unprofitable without MNA.

V. CONCLUSIONS

In this paper, we investigated the economics of multi-network access. Following [1], we found that when MNA is widely adopted, a given network capacity can be realized with much fewer tower and spectrum resources than if MNOs build standalone networks to produce the same combined capacity without MNA. The cost efficiency of MNA is influenced by the way an MNA-capable UE determines which network to attach to. MNA is more efficient, on average, when implemented with an algorithm that chooses the BS that offers higher SINR than with an algorithm that chooses the BS that offers higher expected data rate. The network selection algorithm is particularly influential when the fraction of MNA-capable UEs is low, as is likely the case for a newly established MO-MVNO, and when MNOs' resource allocation scheme prioritizes throughput fairness over total throughput.

While not the only way to implement MNA, an MO-MVNO is the most prevalent form of MNA in the real world today. If all cost savings are passed on to consumers, an MO-MVNO can deliver meaningful savings on the order of 5-10% to its subscribers. It can do so even at a small market share, given an appropriate network selection algorithm. As an MO-MVNO gains market share, it will be able to demand better wholesale prices from partner MNOs, because the resource savings as a result of MNA increase faster than linearly with rising fraction of MNA-capable UEs.

For any operator to decide whether to adopt MNA, it involves complex considerations concerning not only business decisions like investment on infrastructure and spectrum resources, and wholesale pricing, but also technical parameters like network selection algorithms and resource allocation schemes. The minimum wholesale price required to incentivize an MNO to adopt MNA is closely related to whether, and, if so, how, the share of total traffic carried by that MNO changes. There are realistic scenarios where all partner MNOs are willing to offer comparable wholesale prices. But, if an MNO loses traffic share substantially, the value of its saved infrastructure and spectrum resources may not make up for its lost retail revenue, and that MNO may demand a wholesale price much higher than those of the other partner MNOs.

The cost savings from MNA could be more consequential for an MNO with fewer tower and spectrum resources than its competitors because it benefits less from economies of scale, which would make that MNO more inclined to participate in MNA. But exactly how the cost savings are distributed between all participants comes down to negotiation.

Besides economics, there could be regulatory and strategic headwinds to MNA's uptake. Regulators may be wary of MNA for the risk of reduced competition when operators rely on each other to serve consumers. From an operator's perspective, providing its core service by relying on a competitor may sound like a discomforting proposition. Notwithstanding these caveats, the infrastructure and spectrum savings resulting from MNA provide a significant financial incentive for its consideration.

REFERENCES

[1] N. Zhang, J. M. Peha, and M. A. Sirbu, "Expanding Cellular Network Capacity with Multi-Network Access," in *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, 2018, pp. 1–6.

[2] J. M. Peha, "Improving Public Safety Communications," *Issues Sci. Technol.*, vol. 23, pp. 61–68, 2007.

[3] J. M. Peha, "Fundamental Reform in Public Safety Communications Policy," *Fed. Commun. Law J.*, vol. 59, no. 3, pp. 455-456,517-545, 2007.

[4] R. Hallahan and J. Peha, "Policies for Public Safety Use of Commercial Wireless Networks," in *TPRC 2010*, 2010.

[5] J. M. Peha, "A public-private approach to public safety communications," *Issues Sci. Technol.*, vol. 29, no. 4, pp. 37–42, 2013.

[6] R. Hallahan and J. M. Peha, "Enabling Public Safety Priority Use of Commercial Wireless Networks," *Homel. Secur. Aff.*, no. 9, p. Article 13, 2013.

[7] B. Finley and A. Basaure, "Benefits of mobile end user network switching and multihoming," *Comput. Commun.*, vol. 117, pp. 24–35, Feb. 2018.

[8] S. Hua, P. Liu, and S. S. Panwar, "The urge to merge: When cellular service providers pool capacity," in *2012 IEEE International Conference on Communications (ICC)*, 2012, pp. 5020–5025.

[9] J. Kibilda, N. J. Kaminski, and L. A. DaSilva, "Radio Access Network and Spectrum Sharing in Mobile Networks: A Stochastic Geometry Perspective," *IEEE Trans. Wirel. Commun.*, vol. 16, no. 4, pp. 2562–2575, Apr. 2017.

[10] J. S. Panchal, R. D. Yates, and M. M. Buddhikot, "Mobile Network Resource Sharing Options: Performance Comparisons," *IEEE Trans. Wirel. Commun.*, vol. 12, no. 9, pp. 4470–4482, Sep. 2013.

[11] D. Fooladivanda and C. Rosenberg, "Why user swapping could be the best coordination mechanism in a cellular network?," in *2013 IEEE Global Communications Conference (GLOBECOM)*, 2013, pp. 4895–4901.

[12] B. Venkitesh and C. Rosenberg, "Smart Roaming: How Operator Cooperation Can Increase Spectrum Usage Efficiency at Practically No Cost," *IEEE Trans. Netw. Serv. Manag.*, vol. 16, no. 2, pp. 690–700, Jun. 2019.

[13] M. H. Lotfi and S. Sarkar, "The economics of competition and cooperation between MNOs and MVNOs," in *2017 51st Annual Conference on Information Sciences and Systems (CISS)*, 2017, pp. 1–6.

[14] N. Ben Khalifa, A. Benhamiche, A. Simonian, and M. Bouillon, "Profit and Strategic Analysis for MNO-MVNO Partnership," in *2018 IFIP Networking Conference (IFIP Networking) and Workshops*, 2018, pp. 325–333.

[15] J. G. Andrews, F. Baccelli, and R. K. Ganti, "A Tractable Approach to Coverage and Rate in Cellular Networks," *IEEE Trans. Commun.*, vol. 59, no. 11, pp. 3122–3134, Nov. 2011.

[16] R. Mahindra, H. Viswanathan, K. Sundaresan, M. Y. Arslan, and S. Rangarajan, "A practical traffic management system for integrated LTE-WiFi networks," in *Proceedings of the 20th annual international conference on Mobile computing and networking - MobiCom '14*, 2014, pp. 189–200.

[17] E. Aryafar, A. Keshavarz-Haddad, M. Wang, and M. Chiang, "RAT selection games in HetNets," in *2013 Proceedings IEEE INFOCOM*, 2013, pp. 998–1006.

[18] S. Deb, K. Nagaraj, and V. Srinivasan, "MOTA: engineering an operator agnostic mobile service," in *Proceedings of the 17th annual international conference on Mobile computing and networking - MobiCom '11*, 2011, p. 133.

[19] P. Coucheney, C. Touati, and B. Gaujal, "Fair and Efficient User-Network Association Algorithm for Multi-Technology Wireless Networks," in *IEEE INFOCOM 2009 - The 28th Conference on Computer Communications*, 2009, pp. 2811–2815.

[20] K. Zhu, D. Niyato, and P. Wang, "Network Selection in Heterogeneous Wireless Networks: Evolution with Incomplete Information," in *2010 IEEE Wireless Communication and Networking Conference*, 2010, pp. 1–6.

[21] W. Wang, X. Liu, J. Vicente, and P. Mohapatra, "Integration Gain of Heterogeneous WiFi/WiMAX Networks," *IEEE Trans. Mob. Comput.*, vol. 10, no. 8, pp. 1131–1143, Aug. 2011.

[22] D. D. Nguyen, H. X. Nguyen, and L. B. White, "Reinforcement Learning With Network-Assisted Feedback for Heterogeneous RAT Selection," *IEEE Trans. Wirel. Commun.*, vol. 16, no. 9, pp. 6062–6076, Sep. 2017.

[23] Y. Li *et al.*, "Device-Customized Multi-Carrier Network Access on Commodity Smartphones," *IEEE/ACM Trans. Netw.*, vol. 26, no. 6, pp. 2542–2555, Dec. 2018.

[24] L. Zheng, J. Chen, C. Joe-Wong, C. W. Tan, and M. Chiang, "An economic analysis of wireless network infrastructure sharing," in *2017 15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, 2017, pp. 1–8.

[25] L. Zheng, C. Joe-Wong, J. Chen, C. G. Brinton, C. W. Tan, and M. Chiang, "Economic viability of a virtual ISP," in *IEEE INFOCOM 2017 - IEEE Conference on Computer Communications*, 2017, pp. 1–9.

[26] J. M. Peha, "Cellular economies of scale and why disparities in spectrum holdings are detrimental," *Telecomm. Policy*, vol. 41, no. 9, pp. 792–801, Oct. 2017.

[27] T-Mobile US Inc., "Annual Report," 2018. [Online]. Available: http://d18rn0p25nwr6d.cloudfront.net/CIK-0001283699/f46f27cd-c5f9-447c-b6d1-97818a2d3d00.html. [Accessed: 01-Jul-2019].

[28] Cisco, "Cisco Visual Networking Index: Forecast and Trends, 2017–2022 White Paper - Cisco," 2019. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html. [Accessed: 23-Jun-2019].

[29] Google, "Google Fi - Plan benefits & details," 2019. [Online]. Available: https://fi.google.com/about/plan/. [Accessed: 23-Jun-2019].

[30] Mi. Dano, "Special Report—25 charts on spectrum ownership in the United States | FierceWireless," 2018. [Online]. Available: https://www.fiercewireless.com/wireless/25-charts-spectrum-ownership-united-states. [Accessed: 23-Jun-2019].

[31] Crown Castle International Corp., "Annual Report," 2018. [Online]. Available: https://investor.crowncastle.com/node/22611/html. [Accessed: 30-Jun-2019].

[32] Public Safety and Homeland Security, "A Broadband Network Cost Model: A Basis for Public Funding Essential to Bringing Nationwide Interoperable Communications to America's First Responders | Federal Communications Commission," 2010.

[33] Uniti Group Inc., "Annual Report," 2018. [Online]. Available: https://investor.uniti.com/node/9081/html. [Accessed: 30-Jun-2019].

[34] E. Oughton, Z. Frias, T. Russell, D. Sicker, and D. D. Cleevely, "Towards 5G: Scenario-based assessment of the future supply and demand for mobile telecommunications infrastructure," *Technol. Forecast. Soc. Change*, vol. 133, pp. 141–155, Aug. 2018.