To appear on *IEEE Vehicular Technology Conference (VTC)*, Aug. 2018

Expanding Cellular Network Capacity with Multi-Network Access

Nandi Zhang
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, USA
nandiz@cmu.edu

Jon M. Peha
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, USA
peha@cmu.edu

Marvin A. Sirbu
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, USA
sirbu@cmu.edu

***Abstract*—Traditionally, a cell phone remains on a single primary mobile network operator (MNO) as long as it is available, and uses another MNO only when the primary is unavailable and a roaming agreement exists. Multi-network access (MNA), where a cell phone can use any one of multiple MNOs at any point in space and time, can greatly increase cellular network capacity. This paper investigates how much MNA can improve cellular network capacity in the context of a multi-operator mobile virtual network operator (MO-MVNO), such as Google's Project Fi, and explores how the capacity gain varies with the MNOs' resource allocation scheme, and the MO-MVNO's market share and MNO selection algorithm. Simulations show that MNA can expand cellular network capacity by as much as 80% without additional spectrum or infrastructure. Resource allocation schemes affect both total capacity gain and how the gain is shared among operators. We also show that an MNO selection algorithm that is rational for an individual MO-MVNO subscriber can hurt the overall performance of both the MO-MVNO and MNOs.**

Keywords—multi-network access, capacity sharing, MVNO, resource allocation, Google Project Fi

I. Introduction

Traditionally, a cell phone (UE equipment, or UE) has a single mobile network operator (MNO) as its primary service provider and uses the network of another MNO only when the primary is unavailable and a roaming agreement has been established. We consider "multi-network access" (MNA), where a cell phone may at any time be served by the network infrastructure of any one of multiple operators. MNA can increase network capacity significantly. Traditionally, an MNO A subscriber who is far from any MNO A base station (BS) continues to be served by MNO A even if MNO B has a closer BS. Such an arrangement is inefficient because the achievable data rate by a UE depends directly on the SINR, which decreases rapidly as a UE moves further away from the BS. Fewer resource blocks are required to achieve the same data rate for the subscriber, or equivalently a higher data rate can be realized with the same resource blocks, if MNO B serves the subscriber. As long as MNOs do not colocate all their BS's, MNA allows a UE to be served from more locations, and thus, on average, reduces the distance between a UE and its serving BS. Operators can realize higher capacity with less spectrum and/or fewer BS's. This paper quantifies how much capacity gain can be achieved by adopting MNA in a variety of scenarios.

This research was supported by the National Science Foundation Award 1343359 and 1345305.

MNA may take many forms. One example is dual-SIM phones. A more recent example is a multi-operator mobile virtual network operator (MO-MVNO) [1], such as Google's Project Fi wireless service, which leases capacity from two or more facility-based MNOs and intelligently assigns each subscriber to the operator that currently offers the better performance. Going forward, software defined networking (SDN) and network functions virtualization (NFV) in 5G will simplify the leasing of a slice in another operator's network [2] and perhaps make MNA more prevalent. One could imagine a capacity sharing arrangement between two or more MNOs without an intermediary MO-MVNO, in which all parties agree to let each other's subscribers use the network, possibly in exchange for a fee. In this paper, we will focus on the MO-MVNO form of MNA.

Our research shows how the following dimensions affect realizable capacity gain.

Q1: How does the capacity gain from MNA vary with MO-MVNO market share?

The market share of the MO-MVNO(s) represents the fraction of UEs that can use the infrastructure belonging to different MNOs, or are "MNA-capable". The more MNA-capable UEs, the more spectrum resources will be used efficiently and the greater the benefit of MNA.

Q2: How does the capacity gain from MNA vary with the MNOs' resource allocation scheme(s)?

The resource allocation scheme refers to the method by which an MNO BS decides which resource blocks are to be assigned to which UE in each time interval. Resource allocation must trade off between throughput fairness and total throughput. Because MO-MVNO subscribers are on average closer to a BS than MNO subscribers, MO-MVNO subscribers need fewer resource blocks to realize the same data rate. The resource allocation scheme determines how those resource savings are distributed among UEs. A fairness-oriented scheme will distribute saved resources differently from a throughput-oriented scheme.

Q3: How does the capacity increase from MNA vary with an MO-MVNO's MNO selection algorithm?

The MNO selection algorithm refers to the process by which an MO-MVNO UE chooses which BS to attach to at any point in space and time. Globally, the most efficient use of spectrum resources occurs when UEs connect to the BS that offers the highest SINR (typically the closest), but that is not necessarily the best strategy for an individual UE. A UE's nearest BS may offer lower throughput than a BS that is farther away but is less congested, in which case the UE might attach to the farther BS.

Q4: Who benefits more from MNA, MNOs or MO-MVNOs?

We assume MO-MVNOs pay the MNO for the resources they consume. An additional issue is how the efficiency gains of MNA are distributed between MNO and MO-MVNO customers. If an MNO always allocates equal resources to all UEs, MO-MVNO UEs will realize higher data rates than MNO UEs, because they are, on average, closer to the BS. We will consider how the MNO may adjust its resource allocation scheme so that both sets of customers realize the same average data rate.

The rest of this paper is organized as follows. Section II reviews related works. Section III introduces our method and simulation model. Results are presented in Section IV. We conclude in Section V.

II. Related works

Existing literature in this space is of two types: performance implications of MNA, and network selection in Heterogeneous Networks (HetNets). MNA was implied in some of the works on inter-operator resource sharing, which focused on bilateral sharing arrangements between two MNOs. Only a few studies were carried out in the context of an intermediary MO-MVNO that pools capacity from multiple MNOs. We will discuss those works first in Section II. A, and then move on to the broader landscape of inter-operator resource sharing in Section II.B, and lastly review literature on network selection in HetNets in Section II.C.

A. *MO-MVNO*

The possibility of first responders roaming to multiple MNOs was discussed in [3], [4]. The potential for greater total capacity when UEs connect to the BS with the strongest signal regardless of its provider was discussed in [5]–[7]. The term "MO-MVNO" was, to the best of our knowledge, first used in a 2014 UK government report [1] that examines means to improve cellular coverage in rural areas.

Researchers have designed algorithms that allow an MO-MVNO to make better use of multiple MNOs [8], and demonstrated improvements in both throughput and switching latency [9]. Other researchers have explored the economic and welfare implications of an MO-MVNO, and characterized the market equilibrium [10], [11]. We focus instead on how much an MO-MVNO can improve total network capacity in various scenarios.

B. *Performance Implications of Multi-Network Access*

Previous works referred to MNA as "flexible roaming" [12], "infrastructure sharing" [13], [14], or "capacity sharing" [15]. . The authors in [12]–[14] used stochastic geometry (described in [16], [17]) to derive the average UE data rate when MNOs share infrastructure, spectrum, or both. Their models assume randomly distributed BS's. Reference [13], [14] further examined how different spatial distributions of BS's impact the average UE data rate, using clustered BS topology with variable cluster radius to model BS offset and colocation. It was shown that under infrastructure sharing, spatial clustering reduces the achievable average UE data rate. None of these papers considered alternative MNO resource allocation schemes or alternative network selection algorithms. Reference [12] considered only proportional fairness, while [13], [14] assumed what we refer to in this paper as the "Equal-Allocation" scheme.

The authors in [15] performed meticulous simulations to compare the performance of infrastructure sharing, spectrum sharing and sharing on virtualized infrastructure. Infrastructure sharing was shown to perform better than spectrum sharing. Virtualized physical resource block sharing and virtualized spectrum sharing could achieve similar performance to that of infrastructure sharing, but are more complex and costly to implement. However, performance was measured in terms of fewer overloaded sectors and lower packet drop probability, while in this paper we look at network capacity and UE data rate.

C. *Network Selection in HetNet*

The question of how to choose among several possible BS's arises in the context of the radio access technology (RAT) selection problem in heterogeneous networks and is treated in [8], [9], [18]–[25]. The objectives of the proposed algorithms vary, e.g. to maximize throughput, fairness or some measure of utility. A related line of research is concerned with the strategy for assigning UEs to a BS within a single MNO's network, i.e. the UE association problem, from a load-balancing perspective. Reference [26] provides an overview.

Our paper draws on this research to explore a range of selection algorithms to determine how they affect the capacity of networks with MNA-capable devices. The typical scenario of RAT selection problems is a UE attempting to optimize selection of network interface, usually between Wi-Fi or cellular (LTE/WiMax). Our work applies to the selection of service providers at a UE regardless of whether they use the same RAT.

III. Methods and simulation model

A. *Methods and Key Assumptions*

We constructed simulation models in MATLAB with a preset distribution of BS's and UEs, and computed the downlink network capacity when MNOs serve only their own subscribers and when some UEs can use any MNO's BS's.

We assume that each MNO places its BS's on a hexagonal grid. Stationary UEs are uniformly distributed throughout the area. We also assume that UEs have an infinite amount of data to transmit, i.e. a full-buffer traffic model.

We assume each BS has fixed transmit power P_t at reference distance d_0 from the BS. The received power P_r at distance d is calculated by (1), where α is the path loss exponent. Our model does not consider fading.

$$P_r(d) = P_t\left(\frac{d}{d_0}\right)^{-\alpha} \quad (1)$$

We assume that the downlink data rate approaches the Shannon limit. The data rate r_i in bits per second for UE i at distance d from the BS is:

$$r_i = s_i B \log_2\left(1 + \frac{P_r^i}{I + P_n}\right) \quad (2)$$

Here, s_i is the share of spectrum resource blocks assigned to UE i; B is total available bandwidth of each BS in Hz; P_r^i is the received signal power at UE i; I is the sum of interference power from all other BS's, where we have assumed a frequency reuse factor of 1. We also assume a fixed noise floor P_n.

B. Simulation Model

1) Overview

We looked at a scenario of two MNOs and one MO-MVNO. Each MNO has 48 BS's placed on a hexagonal grid in an approximately 10 km by 12 km area that wraps around at the edges. Distance from the BS to a vertex is 1 km. The two hexagonal grids are offset moving on a line perpendicular to the sides of the hexagons, so that each BS of MNO #1 is exactly in the middle of two BS's of MNO #2 (Fig. 1). This configuration provides an upper bound to the potential improvement in capacity. Each BS has $B = 10$ MHz of spectrum available. Transmit power P_t at $d_0 = 1$ meter is 10 Watts. The path loss exponent choice of $\alpha = 3.5$ 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 $P_n = 10^{-13}$ Watts, or -100 dBm.

We assume 4000 customers in total, and each customer subscribes to one of the two MNOs or the MO-MVNO. In the baseline scenario, there is no MO-MVNO subscriber and each MNO has 50% of the customers. We then vary the MO-MVNO's market share from 0% to 100% percent, with the remaining customers split evenly between the two MNOs.

Each UE is apportioned a share s_i of resource blocks, governed by the MNO's resource allocation scheme, which is discussed in the next section.

2) MNO's Resource Allocation Schemes

We constructed an abstract model of resource allocation schemes that allows for varying the tradeoff between throughput-fairness and total throughput. A UE's share of spectrum resources, s_i is given by:

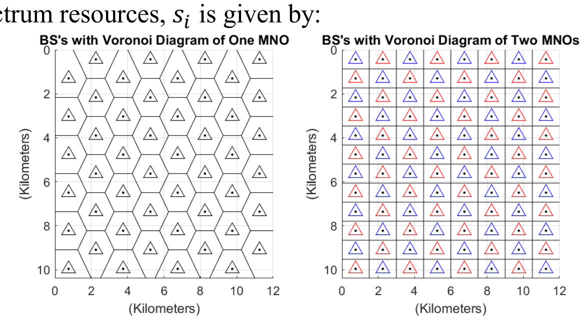

Fig. 1. Map of Base Stations

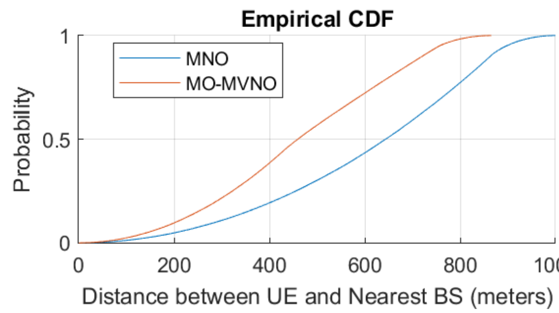

Fig. 2. Cumulative Distribution Function of Distance between Subscriber and Nearest BS

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

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:

- "Equal-Allocation": $\gamma = 0$. Every UE receives an equal fraction of resources. As a result, each UE's throughput can be different due to their varying distances to the BS, though total throughput is higher.
- "Equal-Throughput": $\gamma = -1$. All UEs in a cell get the same data rate. Each UE's share of spectrum resources is inversely proportional to its spectral efficiency at its location.
- "Balanced": $\gamma = -0.5$. This compromise scheme most closely resembles real world MNO practices.

Another aspect of an MNO's resource allocation scheme concerns whether the MNO treats MO-MVNO UEs differently from MNO UEs. The model based on Equation (3) allocates the same amount of resources to all UEs with the same SINR. However, as shown in Fig. 2, MNO UEs are on average farther from a BS than MO-MVNO UEs, and thus are likely to have lower SINR than MO-MVNO UEs. Consequently, MNO UEs on average experience lower data rates than MO-MVNO UEs, except when the "Equal-Throughput" scheme is used. Such performance disparity may put the MNO at a disadvantage, encourage its subscribers to switch to the MO-MVNO, and potentially discourage MNOs from partnering with an MO-MVNO.

To remedy the situation, MNOs could seek monetary compensation from the MO-MVNO for delivering higher throughput. Alternatively, MNOs could modify their resource allocation scheme to give its own subscribers proportionally more resources in order to restore throughput parity, so that average data rate for all MNO UEs equals average data rate for all MO-MVNO UEs. In this work, we adopt the latter solution and introduce another dimension in the resource allocation scheme.

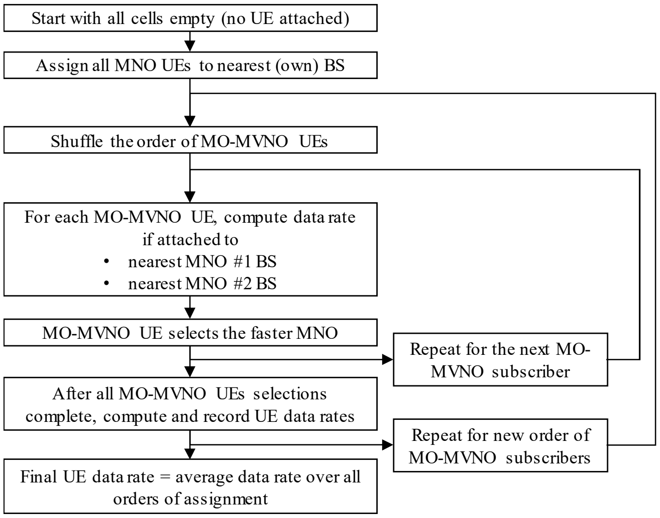

Fig. 3. UE-Cell Association Flowchart for Maximum-Throughput MNO Selection Algorithm

- "Impartial": A BS allocates the same amount of resources to all UEs with the same SINR based on (3).
- "Rate-Adjusted": A BS adjusts resource allocation constant β to equalize the mean data rate among UEs of different operators, given the different distributions of distance and thus SINR.

3) MO-MVNO's MNO Selection Algorithm

We investigate two algorithms an MO-MVNO UE might use to select an MNO.

- "Maximum-SINR": An MO-MVNO UE will attach to (the MNO of) the BS that provides the highest SINR. In our model, this is equivalent to connecting to the nearest BS, because all BS's transmit at the same power level, noise power is constant and we do not consider fading.
- "Maximum-Throughput": An MO-MVNO UE will identify the nearest BS belonging to each MNO and attach to the one that provides greater 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.

For the "Maximum-Throughput" MNO selection algorithm, we assume that UEs select their MNO one at a time, and that they cannot change their selection afterwards. However, the order in which UEs make the selection can change the MNO selected by each UE, and subsequently the data rate. To reduce the effect of selection order on the final data rates, we randomize the order in which MO-MVNO UEs select MNOs, and take the average data rate resulting from each selection order as the final data rate. Fig. 3 is a flowchart of this process.

IV. RESULTS

A. *MNA's Effects on Total Capacity*

MNA can greatly increase network capacity regardless of which resource allocation scheme and which MNO selection algorithm are used. Fig. 4 plots the change in total network throughput of one MNO for various resource allocation schemes and MNO selection algorithms. When the MO-MVNO has 100% market share, each MNO can carry as much as 78% more traffic than in the base case where no UE is capable of MNA. The MNO's network capacity monotonically increases as the MO-MVNO's market share grows, and it increases faster than linearly.

B. *Effects of MNO's Resource Allocation Schemes*

The effects of resource allocation scheme choices are modulated by the MNO selection algorithm being used. When the MO-MVNO's selection algorithm maximizes SINR, (Fig. 4) resource allocation schemes that favor fairness over total throughput experience higher capacity gains. This is expected, because the MO-MVNO removes from an MNO's network UEs that are spectrally least efficient, who thus consume extensive resources when MNOs strive for throughput fairness. That said, even though the "Equal-Allocation" scheme brings a smaller change than "Equal-Throughput", MNA still achieves a healthy gain of as much as 50% over the base case.

Under the "Maximum-Throughput" MNO selection algorithm, the relative positions of the three resource allocation schemes are altered. The "Balanced" scheme dominates, and "Equal-Throughput" now experiences the least relative benefit from MNA.

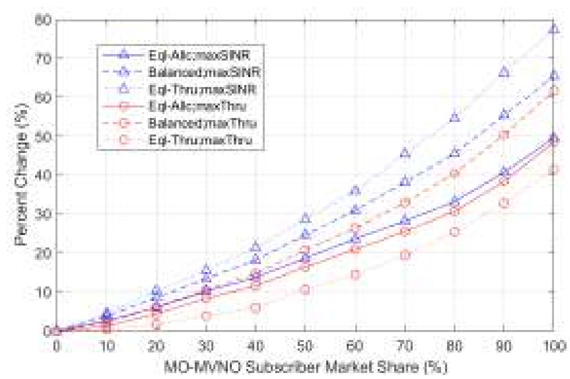

Fig. 4. Percent Change in MNO Network Throughput vs. MO-MVNO Market Share

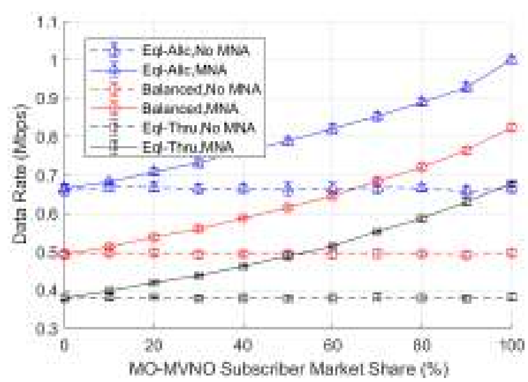

Fig. 5. Average UE Data Rate with Various Resource Allocation Schemes

We should note that, while networks that adopt the "Equal-Allocation" scheme tend to see a smaller relative capacity gain from MNA, they still lead in absolute network capacity, as shown in Fig. 5, because "Equal-Allocation" by design devotes more resource blocks than the other two schemes to UEs with better channel conditions.

C. Disproportionate Gains by Operator

Next we demonstrate how MO-MVNO customers may capture the lion's share of the benefits from MNA and why MNOs may want to preferentially apportion radio resources to their own subscribers to reduce this effect.

Fig. 6 plots the change in average subscriber data rate over the base case as a result of MNA when the MNOs do not distinguish their own subscribers from MO-MVNO subscribers. Because MO-MVNO subscribers are on average closer to a BS and enjoy higher spectral efficiency, they stand to receive a significantly greater performance boost than MNO subscribers, unless the MNOs employ the "Equal-Throughput" resource allocation scheme (not shown) which enforces throughput fairness in each cell. In particular, under "Equal-Allocation", MNO subscribers see no data rate increase while MO-MVNO subscribers claim all the benefits.

Fig. 7 plots the average subscriber data rates resulting from the "Impartial" and "Rate-Adjusted" resource allocation schemes. If the schedulers do not take a UE's subscribed operator into account (solid curves), the MO-MVNO

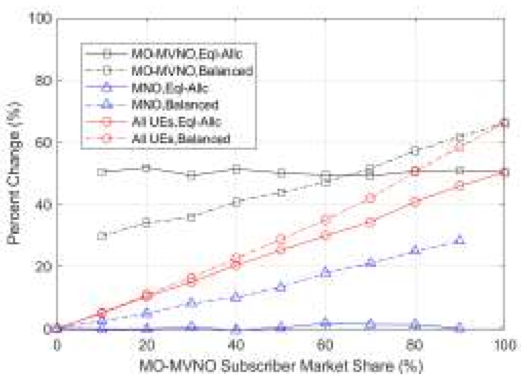

Fig. 6. Change in Average Subscriber Data Rate by Operator ("Impartial" resource allocation, "Maximum-SINR" MNO selection)

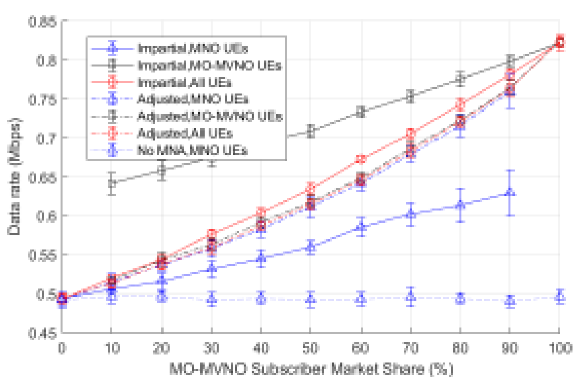

Fig. 7. Average Subscriber Data Rate by Operator vs. MO-MVNO Market Share ("Balanced" resource allocation, "Maximum-SINR" MNO selection)

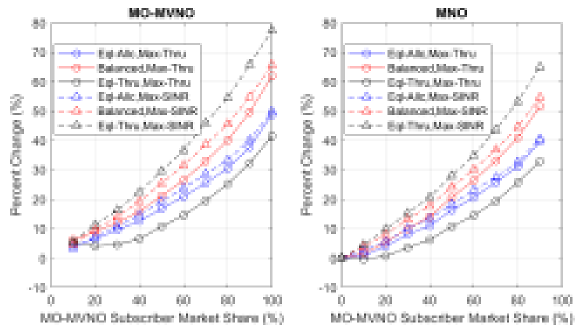

Fig. 8. Change in Average Subscriber Data Rate by Operator ("Rate-Adjusted" resource allocation)

subscribers would receive about 25% higher data rate on average than an MNO's own subscribers. While MNOs may find such disparity troublesome, their subscribers nonetheless see higher data rates than in the base case. In other words, MNA always benefit all operators, although not necessarily equally.

MNOs can adjust their schedulers to provide their own subscribers proportionally more resources to avoid a potential data rate disadvantage (dash-dot curves). However, such an adjustment would incur a slight capacity penalty as it shifts resources to UEs with lower SINR.

D. Effects of MNO Selection Algorithm

Fig. 8 shows that, perhaps surprisingly, the "Maximum-Throughput" selection algorithm consistently yields smaller data rate improvement for any operator than "Maximum-SINR". This is most evident when MNOs enforce throughput-fairness, and holds true for all other resource allocation schemes tested as well. By behaving rationally as an individual UE by choosing the operator that provides the higher data rate, an MO-MVNO subscriber actually hurts the other MO-MVNO subscribers. Always choosing a BS with the highest SINR makes the most efficient use of spectrum. Thus, while an individual MO-MVNO subscriber may be better off forgoing the nearest BS due to local variance in congestion, doing so sacrifices overall system efficiency.

V. CONCLUSIONS

In this paper, we explored the implications of MNA on the capacity of cellular networks. We found that MNA can greatly increase network capacity. When all UEs can utilize multiple networks, the gain in network capacity ranges from 40% to 80%, depending on the exact resource allocation scheme and MNO selection algorithm being used. This benefit monotonically increases with growing fraction of MNA-capable UEs. MNA can expand network capacity without additional spectrum or additional infrastructure, making it more cost-effective for operators to provide a given capacity. However, we note that in an MNA arrangement, operators rely on each other to serve customers, which could reduce competition.

We investigated how the network capacity with MNA is influenced by the process in which an MNA-capable UE selects a BS to attach to. We found that if MNA-capable UEs attach to BS's that offer the highest data rate, similar to the strategy used by Project Fi [27], the average subscriber data rate of any operator is lower than if MNA-capable UEs attach to BS's that provide the highest SINR. In other words, the optimal choice for each individual MO-MVNO subscriber hurts not only the MNOs, but also the MO-MVNO itself. The fact that a simple maximum-SINR selection algorithm is highly effective is encouraging from an implementation perspective, since obtaining precise expected data rate is difficult if not impractical for an MO-MVNO UE.

We looked into how MNOs and MO-MVNOs may differentially benefit from MNA and what role the MNOs' resource allocation scheme plays therein. We found that, even though MNA can improve the data rate when averaged over all UEs, MNO subscribers may see considerably lower data rate than MO-MVNO subscribers, which may be detrimental to the MNOs' business. For an extreme example, when a resource-fair allocation scheme is used, MNO subscribers do not see a higher data rate from MNA at all. We then showed that MNOs can avoid such a disadvantage if they grant their own subscribers proportionally more resource blocks.

REFERENCES

[1] Department for Culture Media Sport, "Tackling Partial Not-Spots in Mobile Phone Coverage," 2014.

[2] J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J. J. Ramos-Munoz, J. Lorca, and J. Folgueira, "Network Slicing for 5G with SDN/NFV: Concepts, Architectures, and Challenges," *IEEE Communications Magazine*, vol. 55, no. 5, pp. 80–87, May-2017.

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

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

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

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

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

[8] L. Yuanjie *et al.*, "iCellular: Device-Customized Cellular Network Access on Commodity Smartphones," *13th USENIX Symp. Networked Syst. Des. Implement.*, pp. 643–656, 2016.

[9] H. Deng *et al.*, "Towards Automated Intelligence in 5G Systems," in *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, 2017, pp. 1–9.

[10] 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.

[11] 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.

[12] 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.

[13] J. Kibilda, P. Di Francesco, F. Malandrino, and L. A. DaSilva, "Infrastructure and spectrum sharing trade-offs in mobile networks," in *2015 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2015, pp. 348–357.

[14] 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.

[15] 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.

[16] 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.

[17] J. Kibilda, B. Galkin, and L. A. DaSilva, "Modelling Multi-Operator Base Station Deployment Patterns in Cellular Networks," *IEEE Trans. Mob. Comput.*, vol. 15, no. 12, pp. 3087–3099, Dec. 2016.

[18] 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.

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

[20] 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.

[21] 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.

[22] 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.

[23] 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.

[24] 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.

[25] L. Wang and G.-S. G. S. Kuo, "Mathematical Modeling for Network Selection in Heterogeneous Wireless Networks — A Tutorial," *IEEE Commun. Surv. Tutorials*, vol. 15, no. 1, pp. 271–292, 2013.

[26] J. Andrews, S. Singh, Q. Ye, X. Lin, and H. Dhillon, "An overview of load balancing in hetnets: old myths and open problems," *IEEE Wirel. Commun.*, vol. 21, no. 2, pp. 18–25, Apr. 2014.

[27] Google, "Frequently asked questions – Project Fi." [Online]. Available: https://fi.google.com/about/faq/. [Accessed: 13-Nov-2017].