Abstract—The licensing model for millimeter wave bands has been the subject of considerable debate, with some industry players advocating for unlicensed use and others for traditional geographic area exclusive use licenses. Meanwhile, the massive bandwidth, highly directional antennas, high penetration loss and susceptibility to shadowing in these bands suggest certain advantages to spectrum and infrastructure sharing. However, even when sharing is technically beneficial (as recent research in this area suggests that it is), it may not be profitable. In this paper, both the technical and economic implications of resource sharing in millimeter wave networks are studied. Millimeter wave service is considered in the economic framework of a network good, where consumers’ utility depends on the size of the network, and the strategic decisions of consumers and service providers are connected to detailed network simulations. The results suggest that “open” deployments of neutral small cells that serve subscribers of any service provider encourage market entry by making it easier for networks to reach critical mass, more than “open” (unlicensed) spectrum would. The conditions under which competitive service providers would prefer to share resources or not are also described.

I. INTRODUCTION

The millimeter wave (mmWave) bands represent one of the largest unlicensed bandwidths ever allocated, presenting a tremendous opportunity for both technical and policy innovation. The appropriate licensing model for this band remains the subject of considerable debate. Replies to an FCC notice of inquiry [1] requesting comments on usage of bands greater than 24 GHz in the United States reveal disagreement on how to best utilize this spectrum, with economic considerations playing a significant role. Major industry players argued in favor of exclusive use licensing on a geographic service area basis, primarily on the grounds that this offers sufficient certainty to motivate major capital investment. Several of these explicitly asked the FCC to reject licensing mechanisms that require spectrum sharing on some bands [2]–[8]. Others argued that unlicensed use maximizes efficient spectrum use, and encourages innovation and competition by lowering barriers to entry [9], [10]. A recent notice of proposed rulemaking [11] for these bands involves 3,850 MHz of spectrum, but does not move on an additional 12,500 MHz of potentially useful spectrum in bands above 24 GHz.

Beyond these business concerns, technical properties of mmWave bands favor spectrum and infrastructure (base station) sharing. While cellular frequencies have traditionally been allocated with geographic area exclusive use licenses, the physical characteristics of mmWave signals suggest that

exclusive use licenses would be sub-optimal in these bands. Specifically, in the mmWave space, the massive bandwidth and spatial degrees of freedom are unlikely to be fully used by any one cellular operator. The use of high-dimensional antenna arrays implies that spectrum can be shared, not just in time, but also in space. Furthermore, mmWave signals observe high penetration loss through brick and glass [12], and are highly susceptible to shadowing. This implies that many more base stations are likely to be needed for wide area coverage, significantly increasing the cost of deployment, thus motivating infrastructure sharing.

However, technological justification for resource sharing does not always translate to economic benefits, for service providers or for consumers. Network service providers are mainly concerned with increasing profit, which is a function of demand, price, and cost. Even when resource sharing improves consumers’ quality of service, it may have a negative effect on the service provider’s profits if it shifts demand to a competing service provider, or if it changes the market dynamics in a way that forces down the price. Similarly, consumers prefer a higher quality of service, but they are also concerned with service availability and price, which could potentially be negatively affected by resource sharing. To gain a fuller understanding of the benefits of resource sharing in mmWave networks, we need to identify the specific impact on quality of service, and then understand how this affects the demand, price, and cost of service.

A. Contributions

The goal of this work is to model the strategic decisions of wireless service providers in building out mmWave networks with or without sharing of spectrum and/or infrastructure. We apply economic models of network goods [13] - products whose value to consumers depends on the number of units sold - to mmWave cellular networks, where the value of the network to the consumer depends on the size of the network (in terms of base station and spectrum resources), and the investment of the service provider in base station and spectrum resources depends on its expected market share. We quantify the positive and negative effects associated with increasing network size, i.e., how a subscriber's data rate changes as the mmWave service provider increases its spectrum holdings, base station deployments, and market share. Using the concept of critical mass [14], we investigate the growth of demand for a mmWave network service under three circumstances: increasing a network from zero size by deploying base stations and licensing spectrum, licensing spectrum but utilizing an
existing deployment of “open” small cells, and deploying base stations but using unlicensed spectrum. We further model the resource sharing decision of competing mmWave service providers as a compatibility problem [15], [16].

The contributions of this work are primarily to connect the performance of mmWave networks to economic models of demand for these network services, as follows:

- We quantify the positive and negative effects of subscribing to a large service provider - one with greater base station density, bandwidth, and number of subscribers - as well as interactions between these. We find a strong positive effect with increasing base station density in a low-SNR regime, but only a weak positive effect with increasing bandwidth. In high-SNR regimes, there is only a weak positive effect with increasing base station density, and this is partially mitigated by a very slight negative interference effect. Moderate-SNR subscribers gain the most from increasing bandwidth and base station density.

- Given these network effects, we consider the effect of “open” resources on new service offerings, where the primary concern of the provider is to establish a stable presence in the market. We find that the slow initial growth of demand at small network sizes makes it difficult for a new provider to reach critical mass. With an existing deployment of “open” small cells, there is robust demand even at small network sizes, which encourages growth. Open spectrum (i.e., unlicensed) does not have as encouraging an effect on market entry.

- We separately consider resource sharing between mmWave service providers who are already established in the market, and are mainly concerned with profit. We apply the economic model of compatibility of network goods to resource sharing in established mmWave cellular networks. We describe a duopoly game involving two vertically differentiated mmWave service providers with and without resource sharing, and quantify the service provider profits and market coverage in each case. We find that providers may prefer to share spectrum and base stations when the market is highly segmented, share base stations when the spectrum is unlicensed, and share spectrum when base stations are all “open”. Otherwise the high-end service provider will prefer not to share resources.

**B. Related Work**

The idea of resource sharing is, of course, not new; a great deal of research effort has been devoted to quantifying the benefits of base station and spectrum sharing in cellular networks. In [17], the authors consider several sharing options for LTE networks, and conclude that an arrangement similar to a traditional roaming agreement offers the best performance with the least complexity for inter-operator sharing. The authors in [18] assess the benefit of sharing both infrastructure and spectrum in the context of a proposed merger between two major cellular operators in the United States, using real base station deployment data to support their claims. In [19] the authors investigate the trade-offs between infrastructure sharing (which improves coverage and has a small positive effect on data rate) and spectrum sharing (which has a positive effect on data rate but reduces coverage probability), and find that combining both kinds of sharing offers the best data rate while partially mitigating the reduced coverage of spectrum sharing. All of these, as well as others [20], [21], conclude that under some conditions, resource sharing increases the capacity of traditional cellular networks, but some find that spectrum sharing without coordination in traditional cellular networks creates interference and degrades performance relative to exclusive use of spectrum by one operator.

Given the unique propagation characteristics of mmWave networks, there has been renewed interest in resource sharing in these bands. mmWave networks will require a denser deployment of base stations than conventional frequencies, increasing the appeal of base station sharing. Industry perspectives on 5G cellular networks [22] suggest a favorable view of neutral small cells owned by a third party and shared by multiple operators. With respect to spectrum sharing, as opposed to conventional cellular frequencies, the inter-cell interference in mmWave bands can be controlled by directional transmissions [23]–[25]. potentially allowing much greater spectrum reuse. In [23], it is shown that with sufficient beam directionality in the transmission pattern, the inter-cell interference is low enough to favor resource sharing even without inter-operator coordination. These conclusions are supported by [26], [27] for different channel models. However, in [25], the authors show that inter-operator coordination is important to users with poor data rates, especially in dense deployments. Similarly, [28] proposes a spectrum sharing scheme with inter-cell coordination to avoid inter-cell interference and increase sharing gain.

With the exception of [19], all of these have considered resource sharing only in the case of symmetric service providers (those with equivalent spectrum and base station resources, and equal market share). On conventional cellular frequencies, [19] shows that resource sharing benefits a large service provider more than a small service provider, because less interference is imposed by the small service provider. However, in mmWave frequencies, where the effect of intercell interference is much smaller, it is not clear whether this result remains relevant.

Furthermore, even when full sharing is strictly beneficial from a technical perspective, competitive dynamics between service providers may discourage sharing unless there are external incentives. With full resource sharing, subscribers of all service providers have exactly the same quality of service, making it difficult for service providers to distinguish themselves in the market and gain market share. None of [19], [23], [25], [26] consider this effect. In [23], the authors claim that with resource sharing, a network operator requires less bandwidth (and therefore, lower spectrum licensing costs) to serve its subscribers with a given median rate. However, this assumes that demand for network services is fixed, then it actually varies according to the quality of service, and it also ignores competition between service providers. The early work on mmWave resource sharing also does not address the case of asymmetric service providers, where the large service provider
contributes more resources to the partnership, but then offers its subscribers the same quality of service as the small service provider.

Some of the literature on cellular networks addresses economic or regulatory aspects of resource sharing. For example, [29] models the tradeoff associated with competition regulation and resource sharing in the context of the planned evolution of cellular networks. A coalition game described in [30] suggests that resource sharing and cooperation can sometimes improve individual cellular service providers’ payoff. A ten-year case study on cellular service providers in Sweden [31] lists incentives, obstacles, and key drivers for cooperation, and a similar investigation of cellular infrastructure sharing in emerging markets is described in [32]. However, none of these address resource sharing in mmWave networks which, as mentioned above, are fundamentally different from previous cellular networks in ways that can affect the decision to share resources or not. An early economic perspective on mmWave networks (although not on resource sharing) in [33] suggests that the limited coverage range of mmWave-based 5G systems is a key challenge for its cost efficiency. Resource sharing could potentially be a way to address this challenge, but the economic implications of resource sharing in mmWave networks have not been studied yet.

C. Paper Organization

The rest of this paper is organized as follows. We begin with a brief introduction to the economic framework used in this paper, in Section II. In Section III we describe the system model and simulation results showing the benefit of resource sharing in mmWave networks with respect to fifth percentile rate. Section IV describes mmWave service as a network good (in the economic sense), and uses simulation results to quantify the network externalities associated with increasing network size. We build on results from Section III and Section IV in Section V to show how demand for mmWave network services evolves as a service provider increases its network size, and we compare the likelihood of market entry with and without “open” resources such as unlicensed spectrum or an open deployment of neutral small cells. In Section VI we describe a duopoly game involving two vertically differentiated mmWave network service providers, and compare their profits with and without resource sharing, for simultaneous market entry and sequential market entry. Finally, in Section VII we conclude with a discussion of the implications of this work and areas of further research.

II. ECONOMIC FOUNDATIONS

We briefly summarize here the economic framework used in the rest of this paper. We define a network good and show how its demand is fundamentally different from demand for non-network goods, give equilibria and conditions for reaching critical mass in a market for a network good, explain the concept of compatibility, and describe a model of vertically differentiated network good. For a more detailed overview of this area of economics, see [13].

A. Network goods

In economics, a network good or service [13] is a product for which the utility that a consumer gains from the product varies with the number of other consumers of the product (the size of the network). This effect on utility - which is called the network externality or the network effect - may be direct or indirect. The classic example of a direct network effect is the telephone network, which is more valuable when the service has more subscribers. The classic example of an indirect effect is the hardware-software model, e.g. a consumer who purchases an Android smartphone will benefit if other consumers also purchase Android smartphones, because this will incentivize the development of new and varied applications for the Android platform. The network externality may also be negative, for example, if an Internet service provider becomes oversubscribed, its subscribers will suffer from the congestion externality.

Fig. 1. An example of demand curves for a series of expected network sizes (dashed lines, each labeled with expected network size $n^e$), and the fulfilled expectations demand curve $p(n; n)$ (solid line), which is the collection of points where the demand curve for an expected network of size $n^e$ intersects the vertical line at $n = n^e$. Three equilibria for a perfectly competitive market with marginal cost $c = 0.1$ are labeled in white text on a dark background, one at $n = 0$ and two at the intersactions of $p(n; n)$ and $p = c$ (dotted line).

A fundamental difference between a network good and one with no network effects is the behavior of the demand curve, which describes the relationship between two key quantities: consumer demand for a good, $n$ (or equivalently, the number of units of the good that are sold i.e., network size), and the price of the good, $p$.

Consider a set of consumers in a market for a non-network good. The total demand for the good, $n$, is normalized so that $n = 1$ when all consumers purchase the good, and $n = 0$ when no consumers purchase the good. A consumers’ willingness to pay for the good is $\omega$, with $\omega$ varying among the set of consumers up to $\hat{\omega}$ (different consumers are willing to pay different prices for an identical good). A consumer of type $\omega$ is indifferent between purchasing the good or not when price $p = \omega$. For $p > \hat{\omega}$, none of the consumers will purchase the good ($n = 0$), because it is too expensive even for consumers with the highest value of $\omega$. At $p = 0$, all of the consumers
will purchase the good \((n = 1)\). The demand curve, which indicates what portion of the consumers will purchase the good at a given price, has a negative slope for most kinds of non-network goods, because the quantity demanded \(n\) (typically shown on the horizontal axis) increases as the price of the good \(p\) (typically shown on the vertical axis) decreases. Conversely, to increase demand for a typical non-network good, a producer of the good must reduce its price. The dashed line labeled “1.0” in Fig. 1 shows a sample demand curve when \(\omega\) is distributed uniformly on the interval \([0, 1]\).

Now let us consider a network good. We still assume heterogenous consumers, with type \(\omega\) up to \(\omega\), but a consumer of type \(\omega\) has willingness to pay \(\omega h(n)\), where \(n\) is the network size, and \(h(n)\) is a network externalities function indicating how consumer utility scales with \(n\). For a positive network externality, \(h(n)\) increases with \(n\), and for a negative network externality \(h(n)\) decreases with \(n\). A consumer purchasing the good at price \(p\) gains utility \(u(\omega, n, p) = \omega h(n) - p\).

Under these circumstances, a consumers’ decision to purchase the good or not depends on how many units of the good they expect will be sold, i.e., the expected network size \(n^e\). A consumer of type \(\omega\) is indifferent between purchasing the good or not when \(p = \omega h(n^e)\). We can draw a demand curve for any expected network size \(n^e\). For \(p > \omega h(n^e)\), none of the consumers will purchase the good \((n = 0)\). For \(p = 0\), all will purchase the good \((n = 1)\). At the point where the demand curve intersects the vertical line at \(n = n^e\), i.e., when the demand for the good at a given price equals the expected network size, we say that consumers’ expectations are fulfilled.

We can construct a series of such demand curves \(p(n; n^e)\) for different values of \(n^e\). Each curve gives the willingness to pay of the \(n\)th consumer when the expected size of the network is \(n^e\). The collection of points at \(n = n^e\), where the actual size of the network and consumers’ expectations regarding the size of the network are the same, then make up the fulfilled expectations demand curve, \(p(n; n^e)\). Fig. 1 shows the fulfilled expectations demand curve \(p(n; n)\) and demand curves for selected values of \(n^e\) when \(h(n) = n\) and \(\omega\) is distributed uniformly on the interval \([0, 1]\).

This fulfilled expectations demand curve gives the size of the network that could be supported at equilibrium for a given price, in the same way that the demand curve for a typical non-network good defines the demand that can be supported at a given price. We notice two key differences between the behavior of the demand curve for a network good and a non-network good.

First, the demand for a network good depends on the consumers’ expected utility, which in turn depends on the expected network size \(n^e\). However, the expected network size depends on consumer demand, creating a self-fulfilling expectation. When many consumers expect the good to be unpopular, they will not purchase the good, and the network size will be small.

Second, we note that although a traditional demand curve always slopes down, the fulfilled expectations demand curve first increases with \(n\), then decreases. That is, for goods with a positive network externality, \(p(n; n)\) first increases with \(n\) due to the network externality, but eventually begins to slope downward, as it becomes increasingly difficult to find customers who have not yet purchased the good, but have a high enough willingness to pay for it. For a traditional good, to gain market share a producer has to reduce the price. For a network good, a producer can sometimes demand a higher price as more units of the good are sold, because the consumers’ utility increases with the number of units sold.

B. Equilibria and critical mass

An important feature of a fulfilled expectations demand curve is how it relates to the size of a network at equilibrium, and particularly, how it relates to the critical mass of the network: the smallest network size that can be sustained in equilibrium [14].

In a monopoly, the producer of the good has no competition to drive down the price. The fulfilled expectations demand curve \(p(n; n)\) defines the price that the producer can charge to sustain demand of size \(n\), earning total revenue of \(np(n; n)\). The producer will choose the network size that maximizes its profits \(\pi(n, p, c) = n(p(n; n) - c)\), where \(c\) is the marginal cost, i.e., the cost to the producer of providing one unit of the good [14].

In a perfectly competitive market, with many producers offering goods that are perfect substitutes, competing producers will drive down the price until it is equal to marginal cost, i.e. \(p(n; n) = c\), yielding three possible equilibria when \(c\) is less than the maximum of \(p(n; n)\):

1) one stable equilibrium at \(n = 0\) (representing a zero size network),
2) an unstable equilibrium for a network of size \(n'\) at the first (smaller \(n\)) intersection of the fulfilled expectations demand curve \(p(n; n)\) with the horizontal line \(p = c\), and
3) a stable equilibrium for a network of size \(n''\) at the second (larger \(n\)) intersection of \(p(n; n)\) and the horizontal \(p = c\).

These are illustrated in Fig. 1. When the line \(p = c\) intersects \(p(n; n)\) once, at its maximum value, there is a stable equilibrium at that point and one at \(n = 0\). When \(c\) is greater than the maximum value of \(p(n; n)\), the producers would only be able to sell the good at a loss, so the only equilibrium will be at \(n = 0\), and no producer will offer the good [14].

It is shown in [14] that under perfect competition, the critical mass is equal to the network size \(n^0\) at which \(p(n; n)\) is maximized. At this point, competing pressures on demand are perfectly balanced. For network sizes between zero and \(n'\), there is “downward pressure” toward the first equilibrium at \(n = 0\), since there are not enough consumers willing to pay for the good at the lowest price at which the producer is prepared to offer it. When \(n' < n < n''\), there are more consumers willing to pay price \(c\), and the service increases in value as more units are sold, exerting “upward pressure” on the demand toward the equilibrium at \(n''\). For \(n > n''\), there is again “downward pressure” on the demand toward \(n''\) because producers are trying to sell the good to the part of the population with a low willingness to pay.
Because of these pressures on demand, \( n'' \) has a strong stability property, and \( n' \) is highly unstable. A producer entering a new market is interested in selling enough units at a small network size for the network to grow to at least \( n' \), since beyond that “tipping point” the upward pressure on demand helps the network reach its non-zero stable equilibrium. The slope of the fulfilled expectations demand curve \( p(n; n) \) for small network sizes is very important, since it describes how easy it is for the network size to reach critical mass. When this slope is large, then for a given value of \( c, n' \) occurs at a smaller network size, making it easier to reach critical mass and from there, the stable equilibrium at \( n'' \).

C. Compatibility

In the previous section, we model a consumer’s willingness to pay for good \( i \) as \( \omega h(n_i) \), where \( h(n_i) \) is the network externalities function and \( n_i \) is the number of consumers who have purchased the good. In this model, \( h(n_i) \) is not affected by the number of units sold of any other good. Now we consider a market where producers may choose to make their goods compatible [15], [16]. When two network goods are compatible, then the total network effect for a consumer of either good is based on the sum network size of both goods, so the network externalities function for good \( i \) is evaluated using the total network size for all the goods: \( h(\sum_{j \in I} n_j) \), where \( I \) is a set of firms producing compatible goods and \( i \in I \).

A firm producing a network good has conflicting incentives for and against compatibility:

- Positive network externalities: A firm that makes its product compatible increases its value to consumers, since the argument to \( h(\cdot) \) is greater.
- Market power: A firm that chooses to make its product incompatible reduces the value of its competitors’ product, so it avoids losing market share, and can charge higher prices.

Compatibility is often used to model a firm’s choice to use a proprietary technical standard or a common industry standard. For example, the developers of a word processing application might choose to use a proprietary file format so that all consumers who need to open these files must purchase their software, or they might choose to use an open standard so that their users can share the files produced with their software with users of other word processors.

D. Vertical differentiation

In our previous model, when two network goods are compatible, consumers prefer them equally, since the value of the network externalities function is the same for both. This can shift demand from one producer to another. A producer may try to distinguish itself from competitors by improving the value of its good in other ways (not by increasing \( n_i \)). For example, consumers of Android-based smartphones benefit from the network effects due to consumers of all Android-compatible smartphones. However, a firm that produces Android phones can distinguish itself in the market by selling handsets with better hardware specifications than its competitors’.

In Section [VI] of this paper, where we consider service providers that are already well established in the market, we use a model of consumer utility described in [34] which includes vertical differentiation. In this model, a consumer’s willingness to pay for good \( i \) is \( \omega q_i + q_i h(\sum_{j \in I} n_j) \), where \( I \) is a set of firms producing compatible goods, \( i \in I \), and \( q_i \) is a scaling factor that represents aspects of the good’s quality that are not a function of the network size. Firms that produce compatible goods can distinguish themselves from one another by choosing different quality levels. However, a firm that chooses to produce a higher-quality good also has higher marginal costs. Where \( c \) was a constant marginal cost in previous sections, now we scale marginal cost according to the quality level, so that the cost to the producer of producing one unit of good \( i \) at quality level \( q_i \) is \( q_i \), and its profits are \( \pi_i(q_i, n_i, p_i) = n_i p_i - q_i n_i \).

E. Application to mmWave network service

Given this economic framework, we are interested in modeling mmWave network service as a network good, to better understand:

- What kind of network effects apply to mmWave network service? What is the relative benefit to a consumer of subscribing to a large service provider? (Section [IV])
- What is the behavior of the fulfilled expectations demand curve for mmWave network service? How difficult is it for a service provider just entering the market to reach critical mass? Do open resources help a service provider reach critical mass? (Section [V])
- Under what conditions will mmWave network service providers want to share resources? Is it desirable for a regulator to enforce resource sharing? (Section [VI])

To answer these questions, we must connect the economic models described in this section to an accurate technical model of mmWave cellular systems, described in Section [III].

III. TECHNICAL BENEFITS OF RESOURCE SHARING

In this section, we describe the system model of the mmWave network used in the rest of the paper. We outline the technical benefits of resource sharing between identical service providers, confirming some of the results of [23], [25]–[27]. We also describe the sharing gains achieved by service providers that are asymmetric with respect to number of subscribers, spectrum holdings, and base station deployments. The simulations of this section will be used in Section [IV] and Section [V] to devise an economic model for mmWave resource sharing.

A. mmWave System Model

We consider a system with multiple mmWave network service providers (NSPs) operating in the 73 GHz band. A service provider \( i \in \{1, \ldots, I\} \) has bandwidth \( W_i \), a set of base stations (BSs) distributed in the network area using a homogeneous Poisson Point Process (hPPP) with intensity
\[\lambda^B_i, \text{ and a set of user equipment (UEs) whose locations are modeled by an independent hPPP with intensity } \lambda^U_i.\]

Both BSs and UEs use antenna arrays for directional beamforming. For the sake of tractability, we approximate the actual array patterns using a simplified pattern as in [24], [25]. Let \(G(\phi)\) denote the simplified antenna directivity pattern depicted in Fig. 2 where \(M\) is the main lobe power gain, \(m\) is the back lobe gain and \(\theta\) is the beamwidth of the main lobe. In general, \(m\) and \(M\) are proportional to the number of antennas in the array and \(M/m\) depends on the type of the array. Furthermore, \(\theta\) is inversely proportional to the number of antennas, i.e., the greater the number of antennas, the more beam directivity. We let \(G^B(\phi)\) (which is parameterized by \(M^B\), \(m^B\), and \(\theta^B\)) be the antenna pattern of the BS, and \(G^U(\phi)\) (which is parameterized by \(M^U\), \(m^U\), and \(\theta^U\)) be the antenna pattern of the UE.

![Fig. 2. Simplified antenna pattern with main lobe \(M\), back lobe \(m\) and beamwidth \(\theta\).](image)

We consider a time-slotted downlink of a mmWave cellular system. The channel model we use includes path loss, shadowing, outage, and small scale fading. For path loss, shadowing, and outage, line of sight (LOS), and NLOS probability distributions, we use models adopted from [36]. We assume Rayleigh block fading. Finally, the data rate is modeled as

\[
R = (1 - \alpha)W \log_2 \left( 1 + \beta \frac{P G^U(0) G^B(0) H}{N_f N_0 W + I} \right),
\]

where \(\alpha\) and \(\beta\) (which are specified in Section III-C) are overhead and loss factors, respectively, and are introduced to fit a specific physical layer to the Shannon capacity curve. Furthermore, \(P\) is the BS transmit power, \(H\) is the channel power gain derived from the model discussed above, and \(N_f\), \(N_0\), \(W\) and \(I\) are UE noise figure, noise power spectral density, bandwidth, and interference power, respectively. We assume perfect beam alignment between BS and UE within a cell, therefore the antenna power gain (link directionality) is

\[
G^U(0) G^B(0) = M^U m^B.
\]

The SINR of a UE is defined as

\[
\frac{P G^U(0) G^B(0) H}{N_f N_0 W + I}.
\]

Let \(B_k\) denote the BS of cell \(k \in \{1, \ldots, K\}\), where \(K\) is the total number of cells. Also, let \(U^k_j\) denote the UE \(j \in \{1, \ldots, N_k\}\) of cell \(k\), where \(N_k\) is the total number of the UEs in cell \(k\). We do not introduce any intercell coordination to manage interference. The power of intercell interference from base station \(B_m\) received at UE \(U^k_j\) depends on the beamwidth \(\theta\), the arrival angle \(\phi_A\) at \(U^k_j\), and the departure angle \(\phi_D\) from \(B_k\), as shown in Fig. 3. In the scenario illustrated we have

\[
I = P G^U(\phi_A) G^B(\phi_D) H_k^m,
\]

where \(H_k^m\) here is the channel gain between \(B_m\) and \(U^k_j\). While the probability of strong intercell interference is low due to the beam directionality, interference still exists. There are four main factors affecting intercell interference:

- **Frequency**: The interference signal is weaker at high frequencies due to path loss [23].
- **Antenna Pattern**: Antenna pattern parameters, especially the beamwidth (\(\theta\) in Fig. 2), directly affect the intercell interference. A larger beamwidth results in stronger intercell interference [23], [24].
- **UE and BS density**: In mmWave networks, strong intercell interference occurs infrequently in sparse networks [24]. This is also true for conventional cellular networks (like LTE), but with the greater beam directionality used in mmWave networks, the network becomes interference limited for much higher UE and BS densities than in conventional networks. However, for ultra-dense deployments, intercell interference can be dominant even with high beam directionalities if there is no coordination [24], [25].
- **Bandwidth**: When the network bandwidth is large, noise power becomes the dominant factor and interference is less important [36].

We consider two kinds of intercell interference. Intra-NSP interference comes from transmissions of neighboring BSs to UEs of the same NSP. Inter-NSP interference comes from transmissions of neighboring BSs to UEs of a different NSP on the same frequency, and occurs only when the service providers use spectrum on a non-exclusive basis.

To model interference, we consider four kinds of resource use:

1. **Exclusive Spectrum, Exclusive BSs (No Sharing)**: Each NSP works independently on its own part of the spectrum, with its own BSs. Obviously, there is no inter-NSP interference. Each UE associates with the closest BS belonging to its own NSP.
2. **Exclusive Spectrum, Non-Exclusive BSs (BS Sharing Only)**: A UE associates with the closest BS, regardless of which NSP it belongs to. As a result, the average distance between a UE and its serving BS is reduced, which leads to a higher received signal power. However, this also increases the intra-NSP interference power relative to the no sharing case, because the distance between the interferer BSs and a UE shrinks along with cell radius. There is no inter-NSP interference.
3) **Non-Exclusive Spectrum, Exclusive BSs (Spectrum Sharing Only):** NSPs use spectrum on a non-exclusive basis. Besides for the increase in noise power due to larger bandwidth, inter-NSP interference also occurs in addition to intra-NSP interference, and these together decrease the SINR of UEs compared to the previous cases, but may still increase the rate.

4) **Non-Exclusive Spectrum, Non-Exclusive BSs (Full Sharing):** NSPs use both spectrum and BSs on a non-exclusive basis. This case is a combination of Case 2 and Case 3.

### B. Scheduling

Early work on resource sharing in mmWave networks [23], [25]–[27] has focused on signal propagation and interference effects in networks with shared resources. To approximate data rate at a UE, these papers divide the link capacity as determined by the UE’s average SINR by the total number of UEs in the cell. In a realistic network with opportunistic scheduling, however, a UE may achieve a higher data rate than its average SINR would suggest, because it is scheduled with higher priority in time slots when its SINR is high. This scheduling gain increases with the number of UEs. For an economic analysis we need to accurately model how consumers’ utility scales with all aspects of network size, including the number of subscribers, so our model must include this scheduling gain.

We adopt a modified scheduler based on the multicell temporal fair opportunistic scheduler proposed in [37]. We use only the first stage (UE nomination stage) of this scheduler, since there is no coordination among the BSs. We expect the difference from the two-stage scheduler with coordination to be negligible, since intercell interference is limited by the directional nature of the transmissions in mmWave networks [27]. Thus each BS runs the scheduler and selects a UE independently, without considering intercell interference and making scheduling decisions based only on the signal to noise ratio of the UEs in each time slot.

### C. Performance Evaluation

In order to establish benefits of resource sharing from a technical perspective, we present simulation results of a mmWave network with two NSPs ($i \in \{1, 2\}$) operating in the 73 GHz band. We fix BS transmit power ($P$) and loss factor ($\beta$) as 30 dBm and 0.5, respectively, as in [36]. Table I shows the specific parameters we use in the simulations. We assume two different cases: **symmetric NSPs** and **asymmetric NSPs**. In the symmetric case, NSPs are identical in terms of network resource (BS density, bandwidth) and UE density. In the asymmetric case, one of the NSPs has more network resources and UE density than the other. Parameters such as UE and BS densities ($\lambda^U_i$, $\lambda^B_i$), and bandwidth ($W_i$) will be specified for each NSP separately.

1) **Symmetric NSPs:** Fig. 4 shows the cumulative distribution function (CDF) of the UE rate, for symmetric NSPs, each with 500 MHz of 73 GHz spectrum licensed for exclusive use, 50 BSs, and 250 UEs in a single square kilometer. All UEs benefit the most from when the NSPs pool both spectrum and BSs. However, both spectrum sharing alone and BS sharing alone improve UE rate relative to the case where no resources are shared. BS sharing has a greater effect on rate than spectrum sharing for UEs outside the coverage range or with a poor signal quality. For UEs in outage, BS sharing improves coverage probability. For UEs with a low SNR, there is little benefit to adding bandwidth because they are in a power-limited regime. UEs with a good signal quality (high SNR) are bandwidth-limited and benefit more from spectrum sharing than from BS sharing. At this BS density (100 BSs total per square kilometer), the effects of interference are negligible due to the directional nature of the transmissions, so there is no negative effect due to spectrum sharing without coordination.

When two NSPs pool their BS and spectrum resources, they offer UEs a higher data rate. This is consistent with the results described in [23], [25]–[27]. However, the early work on mmWave resource sharing in [23], [25]–[27] does not consider NSPs, which we address next.

2) **Asymmetric NSPs:** Fig. 5 shows the CDF of UE rate for consumers of two asymmetric NSPs operating in the same geographic area. The larger NSP has 70% of resources and subscribers: 700 MHz of 73 GHz spectrum licensed for exclusive use, 70 BSs, and 350 UEs in a single square kilometer. The smaller NSP has 30% of resources and subscribers: 300 MHz of spectrum, 30 BSs, and 150 UEs.

When there is no resource sharing, the larger NSP gains market power by offering its subscribers a higher rate than
competing services. With fully shared resources, however, their subscribers’ rate distributions are identical and the services are perfect substitutes. Sharing increases the value of the service that both NSPs offer, but eliminates the ability of the larger NSP to distinguish itself in the market by offering higher rates.

With only spectrum sharing or only BS sharing, the larger NSP retains some ability to differentiate itself in the market by offering higher rates. However, even under these circumstances, the small NSP enjoys greater relative gains than the large NSP from sharing of any kind (compared to no sharing), while the large NSP contributes more resources. The small NSP especially benefits from full sharing or BS sharing by increasing the coverage probability of UEs that were in outage. This gives it an extra competitive edge in the market among consumers who consider stability and coverage probability as a primary factor in choosing their NSP.

IV. mmWAVE SERVICE AS A NETWORK GOOD

In the simulations of Section III we assumed a fixed number of UEs and resources. Now we model mmWave network service as a network good (as explained in Section II), with varying demand and resources. Subscribers benefit from an indirect positive network externality: a large wireless service provider with more subscribers will build a denser deployment of BSs, and purchase more spectrum. (Given large available bandwidth at mmWave frequencies, we expect it will be feasible for NSPs to acquire more spectrum at will.) We describe the impact of increasing network size on consumers’ data rates, using the simulation described in Section III.

The network size $n$ of a mmWave network is defined differently depending on the scenario:

- **No open resources**: In this scenario, an NSP scales its spectrum licenses and BSs according to the number of subscribers it has. Network size, $n$, is the normalized demand for the service, but is also a scaling factor on the BS density ($\lambda^B$) and bandwidth ($W$) of the NSP.

- **Open BS deployment**: In this scenario, there is a pre-existing deployment of neutral small cells, operated by a coalition of service providers or by a third party (as suggested in [22]). These cells have an open association policy, and will serve UEs of any NSP. Network size, $n$, refers to demand for the service and is also a scaling factor on the bandwidth of the NSP, $W$, but the BS density of the NSP is constant and equal to the size of the “open” deployment ($\lambda^B_{\text{max}}$) for all values of $n$.

- **Open spectrum**: In this scenario, spectrum is unlicensed and may be used by any NSP. Here, $n$ refers to demand for the service and is also a scaling factor on the BS density of the NSP, $\lambda^B$. However, the bandwidth of the NSP is constant and equal to the full unlicensed bandwidth $W_{\text{max}}$ for all values of $n$.

Note that the use of “open” resources is not the same as sharing resources acquired by individual NSPs. Open resources are fixed in size and available to all NSPs. Shared resources are also available to participating NSPs, but their size varies according to the network size of the NSPs. Table II enumerates the BS density and bandwidth used by NSP $i$ in all three scenarios, when there is no sharing between individual NSPs and when resources are shared among NSPs in $I$, with $i \in I$. Resources that are used by NSP $i$ on a non-exclusive basis are in bold font.

**TABLE II**

| No open resources | Open BS deployment | Open spectrum |
|-------------------|--------------------|---------------|
| No sharing $\lambda^B_{W_1}$ | $n_1 \lambda^B_{\text{max}}$ | $\lambda^B_{\text{max}}$ | $n_1 \lambda^B_{W_{\text{max}}}$ |
| Sharing $\lambda^B_{W_1}$ | $\sum_{i \in I} n_j \lambda^B_{\text{max}}$ | $\lambda^B_{\text{max}}$ | $\sum_{i \in I} n_j \lambda^B_{W_{\text{max}}}$ |

Depending on the scenario, the total network externality $h(n)$ is the sum of the network effects associated with up to three aspects of $n$. We separately quantify the contribution to $h(n)$ of each:

1) **BS density**: We simulate a network of increasing BS density, with bandwidth constant at 1 GHz and ratio of UEs to BSs constant at 5 UEs per BS. To separately quantify the effect of interference, we also compute
the UE rate based on SNR (neglecting the effect of interference) and compare this to the actual UE rate. These results are shown in Fig. 6.

2) **Bandwidth**: We simulate a network of increasing bandwidth, while keeping BS density constant at a moderate value of 100 BSs per square kilometer, and UE density constant at 500 UEs per square kilometer. These results are shown in Fig. 7.

3) **UE density**: We simulate a network of increasing UE density, while keeping bandwidth constant at 1 GHz and BS density constant at 100 BSs per square kilometer. To quantify the scheduling gain, we also simulate this network with a round robin scheduler, and compare this to UE rate with a partially opportunistic scheduler. These results are shown in Fig. 8.

We assume that consumers decide whether or not to subscribe to a mmWave network based on its fifth percentile rates. This is supported by research on human behavior, which suggests that service reliability is rated more highly than overall connection quality in perceived quality of mobile value-added services [38]. We take fifth percentile rate as a proxy for service reliability.

From Fig. 6, Fig. 7 and Fig. 8, we find that the fifth percentile data rate of UEs is affected by network size as follows:

1) **BS density**: (Fig. 6) As BS density increases, UEs transition between three regions, marked by the vertical lines in Fig. 6. In the outage region on the left, the deployment of mmWave BSs is very sparse, and UEs are likely to be outside the coverage area. In the middle region, increasing BS density improves the probability of having a LOS link, and so the rate grows very quickly with BS density until a point at which virtually all links are LOS. In the third region, there is a smaller marginal benefit associated with higher BS density due to increasing SNR. When the deployment of BSs is extremely dense, there may be a small negative interference effect that partially mitigates the positive effect of increasing BS density, consistent with [25].

2) **Bandwidth**: (Fig. 7) For UEs with a moderate or high SNR, link capacity scales linearly with bandwidth, so these will benefit from subscribing to a large service provider with more mmWave spectrum holdings. However, UEs with a very weak signal power (e.g., in a network where the density of BSs is very low) are power-limited and do not benefit much from increased bandwidth.

3) **UE density**: (Fig. 8) Given a fixed number of BSs, increasing the total number of UEs can overburden the network and create a negative congestion externality. Specifically, when there are $N$ UEs in the cell, each UE is allocated approximately $\frac{1}{N}$th of frequency-time resources. However, because the scheduling of UEs is partially opportunistic, a UE is more likely to be scheduled in high-SINR time periods, and this effect increases with the number of UEs in the cell as the “competition” to be scheduled becomes more intense. Thus with an increasing number of UEs in a cell, an individual UE is scheduled in fewer time slots, but has a higher average data rate in the time slots in which it is scheduled.

In general, the benefit to a UE of increasing any of the three elements of network size discussed above depends on the UE’s signal quality. In sparse deployments, UEs are outside the
coverage area or at its edge, and derive little or no benefit from increasing bandwidth alone. Under moderate SNR conditions, UEs benefit both from increasing BS density and increasing bandwidth. In a very dense network, virtually all UEs have a LOS link and high SNR, and have little to gain from increasing BS density, but benefit from increasing bandwidth.

V. DEMAND FOR MMWAVE SERVICES, WITH AND WITHOUT OPEN RESOURCES

Having quantified the technical effects on fifth percentile rate of increasing mmWave network size in Section IV, we focus on how demand for wireless service, price an NSP can charge, and NSP’s revenue, depend on network size. We are especially interested in the evolution of demand at small network sizes, when an NSP first begins to offer mmWave services, and whether the network will reach critical mass. To address this, we model the willingness to pay of consumers as a function of $n$ (using $h(n)$), then construct a curve of fulfilled expectations demand $p(n; n)$ that shows how demand, price, and revenue scale with $n$. We assume again that consumers decide to subscribe or not based on fifth percentile rates, and consider the three scenarios (no open resources, open BS deployment, and open spectrum) in the “No sharing” row in Table III.

Fig. 9 shows the simulated fifth percentile rate for UEs in a mmWave network, from which we derive $h(n)$ empirically. In the open BS deployment scenario, 100 BSs are available regardless of $n$; in the open spectrum scenario, bandwidth is 1 GHz at all values of $n$. Otherwise, bandwidth, BS density, and the number of UEs in the network scale with $n$ up to 1 GHz, 100 BSs, and 500 UEs, respectively, at $n = 1$. We note that the behavior of the fifth percentile rate is roughly piecewise linear in $n$, with breakpoints when we transition between the SNR regions of Section IV.

Next, we construct a fulfilled expectations demand curve for each of the three scenarios, using the values in Fig. 9 for the network externalities function $h(n)$. We assume consumers are heterogeneous in their willingness to pay for service, and the parameter $\omega$, which denotes the consumer type, is uniformly distributed over $[0, 1]$. A consumer of type $\omega$ subscribing to the network will gain surplus $u(\omega, n, p) = \omega h(n) - p$ from a network of size $n$ at price $p$.

The fulfilled expectations demand curve in Fig. 10 is constructed as described in Section IV. We also show the revenue of the NSP, $np(n; n)$. We observe in Fig. 10 the initially upward-sloping fulfilled expectations demand curve $p(n; n)$ that is a feature of network goods. The slope of this curve at small network sizes is worthy of extra attention. As described in Section IV this determines how easily the network will reach critical mass in a perfectly competitive market where competing networks are homogeneous in every way except for size.

- When there are no open resources, the slope of $p(n; n)$ is small for $0 \leq n \leq 0.262$, suggesting that the marginal benefit of increasing network size is very small when the network size is small. Under these conditions, it is difficult for a network to reach its tipping point.
- When there is an open BS deployment, there is robust demand and strong marginal network externalities even at very small network sizes. Assuming a pre-existing BS deployment, is relatively easy to reach the tipping point under these circumstances.
- With open spectrum, the positive slope of $p(n; n)$ is large for moderate network sizes, but again there is a very small positive slope when $n$ is small ($n \leq 0.235$).

We observe that there is a strong marginal network externality at small network sizes when there is an open BS deployment, and NSPs can grow their network by incrementally adding spectrum holdings and subscribers. This suggests that based purely on the ability of a small NSP to generate revenue (not considering startup costs) and to reach its tipping point, an open BS deployment could ease the barrier to entry for cellular network providers who are considering extending their networks to include mmWave service, encouraging new service offerings. Furthermore, we note that open BSs help encourage new service offerings more than open (shared or unlicensed) spectrum would. However, the open BS scenario relies on a third party having invested in BSs, potentially ahead of demand if there are no existing mmWave NSPs in the market yet and the BSs are only useful for mmWave service. The open spectrum approach relies only on regulators having released the spectrum for unlicensed use in cellular systems.

VI. RESOURCE SHARING IN A COMPETITIVE MARKET

Now we turn our attention to mmWave NSPs that are already established, and are mainly concerned with maximizing their profits in a competitive market, rather than struggling to reach critical mass. We model the NSPs’ decision to share mmWave network resources or not as a compatibility problem (introduced in Section III) where mmWave NSPs are considered compatible if their subscribers can connect to any of the set of NSPs’ BSs, and use a bandwidth equal to their pooled spectrum holdings. We previously addressed the technical benefits of this in Section III. We consider all of the combinations of “shared” and “open” resources in Table III.

In many locations in the United States and around the world, the market for cellular service is effectively a duopoly. We
Fulfilled Expectations
Demand: \( p(n; n) \)
Revenue: \( np(n; n) \)

Thus, if the NSPs share their mmWave network resources, then

\[ 3 \] choose to subscribe to one of the NSPs

\( i \in \{1, 2\} \) or to neither.

The quality \( q_i \) is the \textit{inherent} quality (with maximum feasible value \( \hat{q} \)). It refers to aspects of service unrelated to the size of the mmWave network, such as the quality of voice calls, the quality of the legacy data network, customer service, and the availability of desirable handsets. These measures of quality are increasingly important once the service is well established in the market, and has a sufficiently large network that network size is no longer the single main criterion by which consumers decide which NSP to subscribe to.

An NSP’s marginal costs are increasing in \( q_i \), with cost function \( c(q_i, n_i) = q_i n_i \), and so each NSP \( i \in \{1, 2\} \) seeks to maximize its profits

\[ (2) \]

\[
\pi_i(q_i, n_i, p_i) = n_i p_i - q_i n_i
\]

Consumers evaluate competing services in terms of the difference in their inherent qualities as well as their network externalities. We have heterogeneous consumers parameterized by \( \omega \), with \( \omega \) distributed uniformly from \([0, \hat{\omega}]\). The surplus of a consumer of type \( \omega \) is given by

\[
u(\omega, q_i, \hat{n}_i, p_i) = \begin{cases} \omega q_i + \mu q_i \hat{n}_i - p_i & \text{if subscribes to } i \\ 0 & \text{if no subscription} \end{cases}\]

with \( i \in \{1, 2\} \) and \( 0 \leq \mu < \min[1, \hat{\omega}/2] \), where \( \mu \) is explained in the next paragraph. If the NSPs share their mmWave network resources, then \( \hat{n}_i = \sum_{i \in \{1, 2\}} n_i \), otherwise \( \hat{n}_i = n_i \).

The fifth percentile rate in a mmWave network is piecewise linear in the network size (Fig. 9). Here we consider only moderate- to large-sized networks, where the curves in Fig. 9 are linear. Thus the network externalities function \( h(\hat{n}_i) \) is linear in \( \hat{n}_i \). The scaling factor \( \hat{\mu} \) determines the intensity of the network externality, i.e., \( h(\hat{n}_i) = \hat{\mu} \hat{n}_i \), and is empirically derived from slopes of the lines in Fig. 9.

We consider three scenarios, each with established NSPs:

- **No open resources**: In this scenario we use \( \mu = 0.7 \), corresponding to the slope of the “no open resources” line in Figure 9 for \( n \geq 0.25 \).
- **Open BS deployment**: There is an open BS deployment serving all NSPs. We use \( \mu = 0.25 \), corresponding to the slope of the “open BS deployment” line in Fig. 9 for \( n \geq 0.35 \).
- **Open spectrum**: Spectrum is unlicensed and used by all NSPs. We use \( \mu = 0.4 \), corresponding to the slope of the “open spectrum” line in Fig. 9 for \( n \geq 0.45 \).

By their choice of quality level, the NSPs segment the market into a low-end group (small-\( \omega \) type) and a high-end group (large-\( \omega \) type). Without loss of generality, we say that NSP 1 chooses a higher quality than NSP 2, i.e., \( q_1 > q_2 \), and subscribers of NSP 1 belong to the large-\( \omega \) group. We define two marginal consumers: the consumer of type \( \omega \) is indifferent between choosing no subscription and subscribing to NSP 2, and the consumer of type \( \bar{\omega} \) is indifferent between subscribing to NSP 1 and subscribing to NSP 2.

Then the utility of the marginal consumer of type \( \bar{\omega} \) satisfies

\[
\bar{\omega} q_1 + \mu q_1 \hat{n}_1 - p_1 = \bar{\omega} q_2 + \mu q_2 \hat{n}_2 - p_2
\]

and the utility of the marginal consumer of type \( \bar{\omega} \) satisfies

\[
\bar{\omega} q_2 + \mu q_2 \hat{n}_2 - p_2 = 0
\]

Also, the marginal consumer of type \( \bar{\omega} \) defines the market share of the high-end service

\[
n_1 = \frac{\bar{\omega} - \bar{\omega}}{\bar{\omega}}
\]

and the marginal consumers together define the market share of the low-end service

\[
n_2 = \frac{\omega - \omega}{\bar{\omega}}
\]

We can solve (4), (5), (6), and (7) for \( n_1, n_2, \bar{\omega}, \) and \( \omega, \) and thus determine the decisions of the consumers and the market share of each NSP given \( p_i, q_i, i \in \{1, 2\} \).
Given \( p_i \) and \( q_i \), \( i \in \{1, 2\} \), it is shown in [34] that if the ratio of quality levels satisfies
\[
\frac{q_1}{q_2} > \left( \frac{\hat{\omega}^2}{(\omega - \mu)(\omega - 2\mu)} \right) \tag{8}
\]
then there is a unique Nash equilibrium in which both NSPs set prices higher than their marginal costs. Furthermore, if the solution to (4), (5), (6), and (7) satisfies
\[
0 < \omega < \bar{\omega} < \hat{\omega}
\tag{9}
\]
then both NSPs have market share greater than zero. When both (8) and (9) hold, then there is a unique Nash equilibrium in which both NSPs earn non-zero profit. We restrict our attention to these circumstances, since these are of primary interest to us.

If (8) and (9) hold and the NSPs do not share resources, then according to [34] their equilibrium prices \( p^*_1,NS, p^*_2,NS \) as are:
\[
p^*_1,NS = q_1 \left[ 1 + \frac{(\hat{\omega} - 1)((\omega - \mu)^2 - q_2(\hat{\omega}(\omega - 2\mu)))}{4q_1(\omega - \mu)^2 - q_2\omega^2} \right] > q_1 \tag{10}
\]
\[
p^*_2,NS = q_2 \left[ 1 + \frac{((\hat{\omega} - 1)q_2(\omega - \mu)(\omega - 2\mu) - q_2\omega^2)}{4q_1(\omega - \mu)^2 - q_2\omega^2} \right] > q_2 \tag{11}
\]
and their equilibrium quality levels \( q^*_1,NS, q^*_2,NS \) are:
\[
q^*_1,NS = \hat{q} \tag{12}
\]
\[
q^*_2,NS = \frac{\hat{q}(\omega - \mu)(\sqrt{3(3\omega + 3\omega^2 - 2\omega\mu)} - 3\omega + 3\omega^2) - 2(\omega - \mu)^2}{2\omega^2(7\omega - 5\mu)} \tag{13}
\]

The profits of the high-end NSP always increase with \( q_1 \), so it will use \( \hat{q} \). The low-end NSP sets \( q_2 \) to balance two competing effects: at high values of \( q_2 \) the low-end NSP has a greater market share, but is also more similar to \( q_1 \), which increases price competition and drives the price of service down.

Note that reducing the parameter \( \hat{q} \) increases price competition, since the difference in quality levels between NSPs will be small and so consumers’ decisions will be more sensitive to price. Similarly, reducing \( \hat{\omega} \) increases price competition, since this decreases the dispersion of consumers’ willingness to pay and the market is less segmented.

If the NSPs share resources, then per [34] their equilibrium prices \( p^*_1,S, p^*_2,S \) are:
\[
p^*_1,S = q_1 \left[ 1 + \frac{2\hat{\omega}(\omega - 1)(q_1 - q_2)}{(4\omega - 3\mu)q_1 - \omega q_2} \right] > q_1 \tag{14}
\]
\[
p^*_2,S = q_2 \left[ 1 + \frac{\hat{\omega}(\omega - 1)(q_1 - q_2)}{(4\omega - 3\mu)q_1 - \omega q_2} \right] > q_2 \tag{15}
\]
and their equilibrium quality levels \( q^*_1,S, q^*_2,S \) are:
\[
q^*_1,S = \hat{q} \tag{16}
\]
\[
q^*_2,S = \frac{\hat{q}(4\omega - 3\mu)}{7\omega - 6\mu} < \hat{q} \tag{17}
\]

For the sake of comparison, we are also interested in the profits of a monopoly NSP. When there is only one NSP, the marginal consumer is defined by
\[
\bar{\omega}q_1 + \mu q_1 n_1 - p_1 = 0 \tag{18}
\]
and the market share of the NSP is
\[
n_1 = \frac{\bar{\omega} - \omega}{\omega} \tag{19}
\]

At equilibrium, the monopoly NSP will choose price
\[
p^*_1,M = \frac{q_1(\bar{\omega} - 1)}{2} \tag{20}
\]
and quality level
\[
q^*_1,M = \hat{q} \tag{21}
\]

Fig. 11 shows the profits of each NSP in various circumstances, as \( \omega \) (and dispersion of consumers’ willingness to pay) increases. First, we note that the low-end NSP always prefers to share resources. Since it captures the low end of the market (the consumers who are less willing to pay for inherent quality), the network effects are especially important to this NSP. In the duopoly market, the high-end NSP paradoxically prefers to share resources when the intensity of the network effect is small (as when there are open resources), because its competitor gains less of an advantage from the larger (shared) network size. (This is consistent with the results described in [16]). When the intensity of the network effect is large (as it is when there are no open resources) then the high-end NSP prefers resource sharing only when the market is highly segmented and there is little price competition (i.e., for large \( \hat{\omega} \)).

Fig. 12 shows the market share of each NSP and total market coverage (i.e., share of consumers who subscribe to either NSP) under the same set of circumstances. When \( \omega \) (and the dispersion of consumers’ willingness to pay) is small, sharing offers the best overall market coverage. When \( \omega \) is large, the best market coverage is achieved by not sharing resources. The value of \( \omega \) at which the benefit of market segmentation begins to dominate the benefit of network effects is greater when the intensity of the network effect is high (large \( \mu \)).

VII. CONCLUSIONS

In this paper, we have connected economic models of the strategic decision making of cellular network service providers and subscribers, to detailed simulations of mmWave networks, with and without resource sharing. While we have confirmed the benefits of resource sharing from a purely technical view (without considering the effect on demand), with the economic analysis we have illustrated that resource sharing is not always the preferred strategy of service providers, and some kinds of resource sharing may be preferred over others. We have shown that “open” deployments of neutral small cells make it easier for networks to reach critical mass, encouraging market entry more than “open” spectrum would. Furthermore, we have shown that the leading service provider in a duopoly market prefers to share resources only when sharing gains are small or the market is highly segmented. Our technical simulations of asymmetric service providers have hinted at this, with
greater gains for the smaller service provider than the market leader. However with a purely technical approach, one would conclude that resource sharing is always beneficial (albeit less beneficial for the market leader), while the economic analysis with consideration of price and demand in addition to technical gains has suggested a different conclusion.

We briefly discuss here some assumptions of our approach. Our results are predicated on an assumed indirect network effect benefitting consumers subscribing to a large service provider. That is, we assume that the resources held by a service provider in a given market scale together with the number of subscribers it serves. Practically, building out physical infrastructure and licensing spectrum requires a tremendous capital investment. A service provider is unlikely to build out a very large network, at great cost, when it has few subscribers and so a limited revenue stream. For this reason, we consider it justified to tie the level of investment in the network - and thus, the size of the network resources - to the number of subscribers. Another assumption is that consumers are homogeneous in their preference for one firm or the other, given their overall valuation of network service, i.e., that consumers with the same $\omega$ will make the same choice between service providers, given their price, network size, and inherent quality. Actually, consumers and are not identical between service providers, given their price, network size, and inherent quality. However, despite this common simplifying assumption, the general economic framework we have applied in this paper has been empirically validated in a variety of other industries with network effects.

The work in this paper suggests several interesting avenues for further research. We would like to extend this model to include the investment costs associated with deploying a new mmWave network, which we expect to be substantially different from traditional cellular networks given the unique physical characteristics of the mmWave bands. We would also like to investigate scheduling strategies that divide shared resources among mmWave service providers in ways that increase the benefit of resource sharing for both service providers and consumers.

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