

Capturing Capacity and Profit Gains with Base Station Sharing in mmWave Cellular Networks

Shahram Shahsavari, Fraida Fund, Elza Erkip, Shivendra S. Panwar
Department of Electrical and Computer Engineering
NYU Tandon School of Engineering
{shahram.shahsavari,ffund,elza,panwar}@nyu.edu

Abstract—Due to the greater path loss, shadowing, and increased effect of blockage in millimeter wave cellular networks, base station sharing among network service providers has the potential to significantly improve overall network capacity. However, a service provider may find that despite the technical gains, sharing actually reduces its profits because it makes price competition between service providers tougher. In this work, a weighted scheduling algorithm is described, which gives greater control over how the airtime resource is allocated within a shared cell. It is shown that, under certain market conditions, there exist scheduling weights such that base station sharing is more profitable than not sharing for both service providers in a duopoly market, while still achieving almost as much network capacity as in a conventional base station sharing scenario. Thus, both technical and economic benefits of base station sharing may be realized simultaneously.

I. INTRODUCTION

Compared to conventional microwave frequencies, millimeter wave (mmWave) frequencies have several properties that suggest greater technical benefits due to spectrum and base station sharing among cellular network service providers. The massive bandwidth available at mmWave bands is unlikely to be fully utilized by any one service provider, and the narrow beamwidth of mmWave signals decreases the likelihood of interference due to uncoordinated spectrum sharing. Meanwhile, the greater path loss and increased spatial degrees of freedom necessitate a dense deployment of base stations, which may be costly for a single service provider.

Early results in the literature suggest that in fact, mmWave cellular networks can benefit on a technical level from resource sharing [1]–[4]. Under certain conditions (e.g. sufficiently narrow beamwidth and low enough base station density) the network capacity and the data rate experienced by most users are higher when service providers share base stations and spectrum, even without coordination. Some have suggested that these technical gains may translate to economic gains. For example, [1] claims that it is economical for mmWave service providers to share resources because they can offer the same quality of service while licensing less spectrum, while [2] points out savings on costs including both spectrum licensing and base station deployment. Similarly, [4] suggests that a mmWave spectrum holder can earn additional revenue by licensing the spectrum in a secondary market with the condition of restricted interference to its own users.

However, even if service providers can reduce costs or earn revenue from secondary licensing while keeping quality of

service the same, resource sharing can affect 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. Our previous work [5] suggests that mmWave cellular service providers may be *less* likely to consider sharing resources in a competitive market. In mmWave cellular networks, a service provider with a large network (i.e. having more spectrum and base stations) has a considerable advantage over a smaller service provider - much more so than in an equivalent microwave network. With resource sharing, the large service provider would lose this considerable competitive advantage and would have to deal with stiffer price competition, and so would be unwilling to consider resource sharing under certain market conditions. Furthermore, a service provider with a large network typically finds that it stands to gain much less from pooling resources with a small service provider, than the small provider does. Thus, we find that with standard base station sharing, it is difficult to capitalize on both technical and profit gains at the same time.

To address this issue, we turn to cooperative game theory, where we find several methods for distributing the profits of a coalition in a weighted manner among its members. These methods have also been used to allocate network or computational resources in various settings [6]–[9]. In this work, we explore the feasibility of using a similar approach to allocate airtime within a wireless cell among members of a coalition of network service providers that share base stations, with the goal of finding a resource allocation scheme under which both technical and profit gains may be realized.

The contributions of this work are as follows:

- We describe a scheduling approach that allows for control over how airtime is allocated among users in a shared cell, so that it can be weighted according to the relative contributions (in terms of base stations) of the network service providers to which they subscribe. We show that with this scheduling approach we can achieve almost all of the efficiency gains associated with resource sharing, while still preserving a difference in quality of service between service providers.
- We formulate a simple resource sharing game, and show that in a competitive duopoly market for mmWave cellular service, network service providers may be willing to share base station resources with our proposed scheduler.

The rest of this paper is organized as follows. First, in Section II, we propose an approach to scheduling that weighs users of different network service providers according to their contributions to the pool of shared resources. Next, in Section III, we show through simulations that with this scheduler we can achieve almost the full technical sharing gains (i.e. overall network capacity) while still distinguishing between network service providers in terms of the quality of service offered to subscribers. In Section IV, we model a simple duopoly market as a game, and show that, under certain conditions, both service providers in the market earn higher revenue while sharing resources using the weighted scheduler. Finally, in Section V we conclude with discussion and suggestions for future work.

II. SCHEDULER FOR WEIGHTED RESOURCE SHARING

We consider a system with a set of wireless base stations (BSs), users, and NSPs. Each BS is operated by one network service provider (NSP), and each user subscribes to one NSP. When there is no base station sharing, each user is served by the closest BS operated by the NSP to which it subscribes. However, when NSPs form a coalition to share base stations, then their subscribers can be served by the closest BS that is operated by an NSP that is a member of the coalition. All BSs use the same unlicensed spectrum, regardless of whether or not they are shared.

In this section, we propose a scheduler for allocating downlink time slots in a shared wireless cell serving users of multiple network service providers, that satisfies the following design goals:

- The scheduler is opportunistic, so that it can take advantage of the multi-user diversity that is a major factor in the sharing gains observed in mmWave cellular networks.
- It is temporal fair, so that in the long term, the airtime allocated to each user will converge to a predefined share of the total airtime.
- By setting the predefined shares, we can differentiate between subscribers of multiple NSPs so that a large NSP can maintain some competitive advantage.

We adopt a modified scheduler based on the multicell temporal fair opportunistic scheduler proposed in [10]. At each time slot, the scheduler selects a user $j^* = \operatorname{argmax}_j (R_j + \gamma b_j)$, where R_j denotes the estimated data rate of the user j (using a pilot sequence) and b_j is a credit parameter updated as $\forall j : b_j = b_j + a_j - \mathbb{1}_{\{j=j^*\}}$ to achieve long-term temporal fairness among the users. This scheduler guarantees that the temporal share of user j (i.e. the fraction of the time slots in which user j is chosen) converges to a predefined weight a_j ($\sum_j a_j = 1$) while exploiting the multi-user diversity to increase the total throughput in the cell [10]. In other words, this scheduler can be viewed as an opportunistic fair credit-based procedure where selected (not selected) users lose (gain) credit and the algorithm parameter $\gamma \geq 0$ is the weight of the credit component. For very large γ , this scheduler is equivalent to a round robin scheduler because the users are chosen almost only based on their credit parameter. On the other hand, for

$\gamma = 0$ the scheduler is purely opportunistic and does not offer temporal fairness.

The operation of the scheduler depends on the base station sharing scenario:

- **No base station sharing:** all users in a cell are assigned the same weight $a_j = \frac{1}{N_i}$, where N_i is the number of subscribers in the cell. All users in the cell subscribe to NSP i , since with no BS sharing, users are only served by a base station operated by the NSP to which they subscribe. A user is not necessarily served by the closest base station.
- **Equal sharing:** BSs are shared by a set of NSPs I . In each shared cell, all users in the cell are assigned the same weight $a_j = \frac{1}{N_I}$, where N_I is the number of subscribers (of any NSP in I) in the cell.
- **Weighted sharing:** BSs are shared by a set of NSPs I . In each shared cell, users are assigned weights $a_j = \frac{\psi_i}{N_i}$, where ψ_i is the weight assigned to NSP $i \in I$, $\sum_{i \in I} \psi_i = 1$ and user j subscribes to NSP i .

Note that the total number of BSs in the system, and the total number of users, is fixed, but cell boundaries are different depending on whether BSs are shared or not. When BSs are shared, users may be served by a closer BS, so the average coverage area of a cell will decrease while the average number of users served remains the same.

In the weighted sharing scenario, airtime is not equally shared among all users in a cell, but is allocated based on a per-NSP parameter ψ_i . This parameter can be adjusted in order to differentiate between subscribers of different NSPs. In Section IV, we will show that for certain values of ψ_i , weighted sharing may be mutually beneficial for NSPs in a duopoly market.

III. NETWORK SIMULATION

In this section, we show by means of simulation that in the weighted sharing scenario, we can achieve almost the same sharing gains observed for the equal sharing scenario in a mmWave cellular network. First, we describe the system model underlying the simulations. Then, we show simulation results for a network with two symmetric NSPs (same density of base stations and subscribers) and several networks with two asymmetric NSPs.

A. Technical system model

Our simulation captures the following key characteristics of mmWave networks:

- **Channel model:** We use the empirically derived line of sight (LOS), NLOS and outage probabilistic channel models for mmWave links from [11].
- **Directional transmission:** We use the antenna pattern model described in [12] with model parameters representing an 8x8 antenna array at the BS and a 4x4 antenna array at the user.

We consider a system with two NSPs, with a system model similar to [5]. Each NSP $i \in \{1, 2\}$ has BSs distributed in

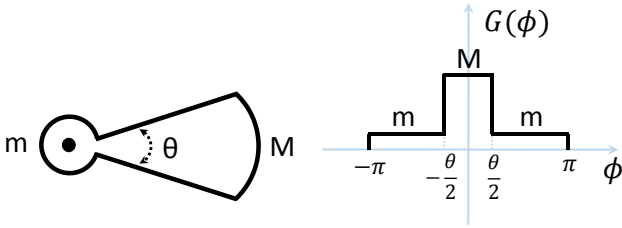


Fig. 1: Simplified antenna pattern with main lobe M , back lobe m and beamwidth θ .

the network area using a homogeneous Poisson Point Process (hPPP) with intensity λ_i^B , and users whose locations are modeled by an independent hPPP with intensity λ_i^U . Also, both NSPs use the same frequency band with bandwidth W . Although it is possible to have strong interference due to the shared frequency with no coordination, the narrow beamwidth, increased channel loss, and large bandwidth (hence large noise power) in mmWave networks means that noise and not interference is usually the dominant effect [11].

Both BSs and users use antenna arrays for directional beamforming. We approximate the actual array patterns using a simplified pattern as in [12]. Let $G(\phi)$ denote the antenna directivity pattern depicted in Fig. 1, where M is the main lobe power gain, m is the back lobe gain and θ is the beamwidth of the main lobe. In general, m and M are dependent on the number of antennas in the array and M/m depends on the type of the array. Furthermore, θ is inversely proportional to the number of antennas, i.e., the greater the number of antennas, the more beam directionality. We let $G^B(\phi)$ (which is parameterized by M^B , m^B , and θ^B) be the antenna pattern of the BS, and $G^U(\phi)$ (which is parameterized by M^U , m^U , and θ^U) be the antenna pattern of the user.

We model a time-slotted downlink of a cellular system. For path loss, shadowing, and outage, line of sight (LOS), and NLOS probability distributions, we use models adopted from [11]. We assume Rayleigh block fading to model small scale channel variations. The data rate is modeled as

$$R = (1 - \alpha)W \log_2 \left(1 + \beta \frac{PG^U(0)G^B(0)H}{N_f N_0 W + Y} \right), \quad (1)$$

where α and β are overhead and loss factors, respectively, and are introduced to fit a specific physical layer to the Shannon capacity curve [11]. Furthermore, P is the BS transmitting power, and H is the channel power gain derived from the model discussed above, incorporating the effects of fading, shadowing, outage, and path loss. We assume perfect beam alignment between BS and user device within a cell, therefore the antenna power gain (link directionality) is $G^U(0)G^B(0) = M^U M^B$. Finally, N_f , N_0 , W and Y are user device noise figure, noise power spectral density, bandwidth, and interference power, respectively.

B. Results

Using the model described in the previous subsection, we simulate a mmWave network with the parameters given in

Table I.

TABLE I: Network parameters

Parameter	Value
Frequency	73 GHz
Bandwidth (W)	1 GHz
Total BS density ($\lambda^B = \sum_{i \in \{1,2\}} \lambda_i^B$)	100 BSs/km ²
Total user density ($\lambda^U = \sum_{i \in \{1,2\}} \lambda_i^U$)	500 UEs/km ²
BS transmit power P	30 dBm
(M^B, m^B, θ^B)	(20 dB, -10 dB, 5°)
(M^U, m^U, θ^U)	(10 dB, -10 dB, 30°)
Simulation area	1 km ²
Rate model (α, β)	(0.2, 0.5)
User device noise figure (N_f)	7 dB
Noise PSD (N_0)	-174 dBm/Hz
Scheduler parameter (γ)	0.01

We simulate a network with two NSPs, and a fixed number of BSs and users divided among the NSPs according to their relative size n_i . An NSP i has BS density $\lambda_i^B = n_i \lambda^B$ and user density $\lambda_i^U = n_i \lambda^U$. We consider the case of symmetric NSPs ($n_1 = n_2 = 0.5$) and two cases of asymmetric NSPs ($n_1 = 0.6, n_2 = 0.4$ and $n_1 = 0.7, n_2 = 0.3$).

The simulation results are shown in Figure 2. Figure 2a shows the average user throughput. Figure 2b shows the throughput for each NSP separately, as well as their sum.

The average user throughput is higher with equal sharing than with no sharing for users of both NSPs (Figure 2a). However, even in an asymmetric scenario, where one NSP contributes more base stations to the pool of shared resources than the other, users of both NSPs can expect exactly the same average throughput. The larger NSP loses any competitive edge it had in the market, which disincentivizes base station sharing despite the higher average data rate experienced by its users. With weighted sharing, however, ψ_1 (and consequently, ψ_2) can be adjusted so as to preserve a distinction in the quality of service offered to users of different NSPs. In Section IV we will show that for some market scenarios, there are values of ψ_1 and ψ_2 with which weighted sharing is mutually beneficial for both NSPs.

Meanwhile, considering the average cell throughput (Figure 2b), we note that in the weighted sharing scenario the total throughput achieved by NSP 1 and NSP 2 together, is almost as high as in the equal sharing scenario. The equal sharing scheduler is slightly more opportunistic than the weighted sharing scheduler, leading to higher overall throughput. However, in the weighted sharing scenario, the network still benefits from greater BS diversity and multiuser diversity than when there is no sharing at all, capturing most of the potential sharing gains.

IV. SIMPLE DUOPOLY GAME

We have shown in Section III that with the weighted sharing scheduler, mmWave NSPs can benefit from technical sharing gains (achieve an overall network capacity similar to equal sharing) while still preserving a competitive difference in user quality of service. This has the potential to create market dynamics that are more favorable to resource sharing. In this

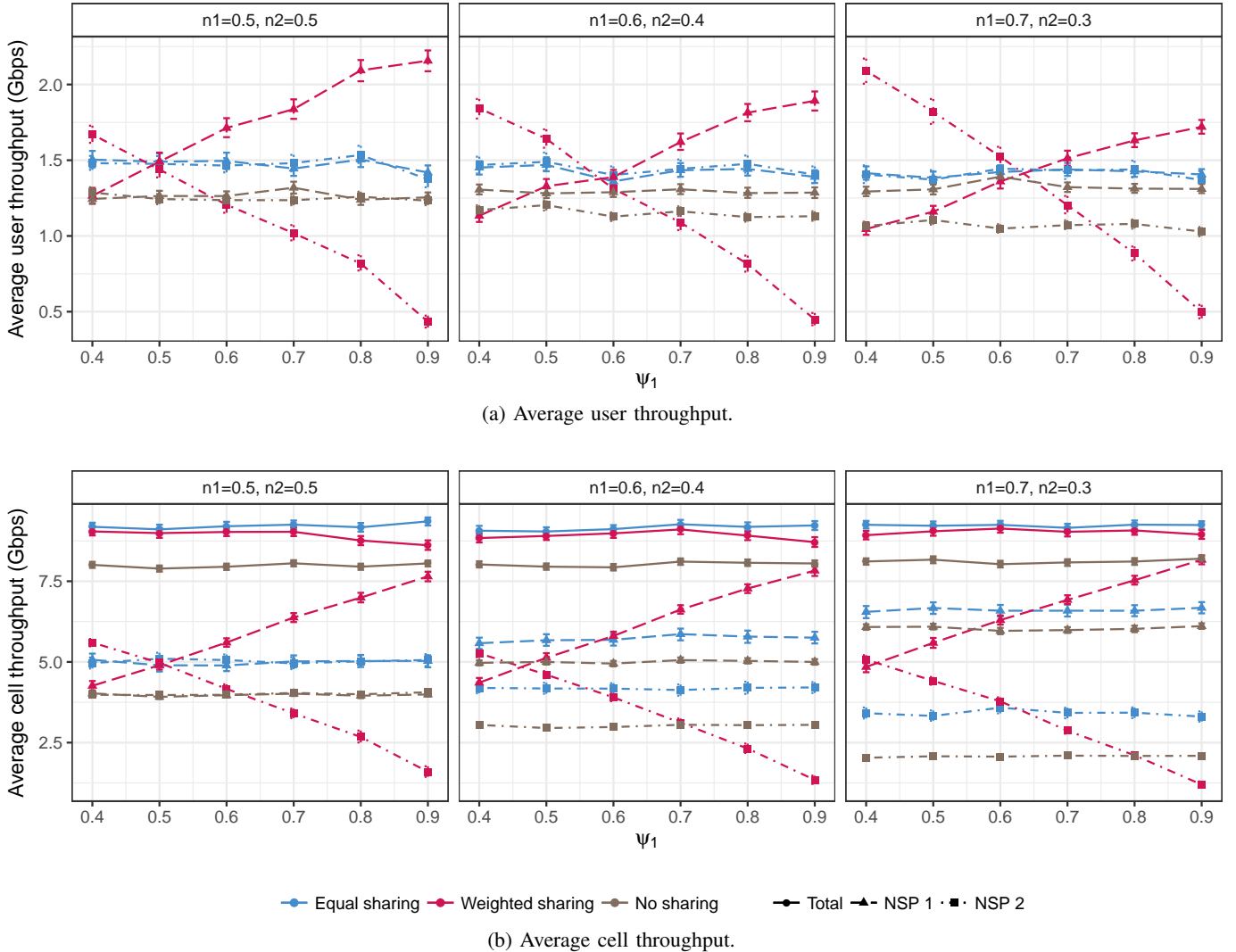


Fig. 2: Average user and cell throughput in three sharing scenarios - no sharing, equal sharing, and weighted sharing - for symmetric and asymmetric NSPs. The share of the total number of BSs belonging to NSP 1 and 2, n_1 and n_2 respectively, are shown at the top of each panel. In the lower plot, we also show the total average throughput achieved by NSP 1 and NSP 2 together within one cell, in addition to the individual throughputs measured by each NSP within the cell. The horizontal axis shows how throughput varies with ψ_1 , the weight assigned to (the larger) NSP 1 in the scheduler. Error bars show 95% confidence intervals. For the scenarios with equal sharing or no sharing, the throughput is flat with only minor variation within the confidence intervals.

section, we investigate a simple duopoly market and show that under some market conditions where equal sharing is not mutually beneficial to both NSPs, weighted resource sharing may be. In those markets where weighted sharing can be mutually beneficial, we also give the range of ψ_1 and ψ_2 for which both NSPs earn higher profits with weighted sharing than with none.

A. Scenario

We consider a simple duopoly game involving three players: a set of consumers, a dominant NSP 1 with size n_1 , and a smaller NSP 2 with size $n_2 < n_1$ where n_i represents the

share of base stations operated by NSP i . The game is played in three stages:

- 1) NSP 1 sets the price of its service, p_1 .
- 2) NSP 2 sets the price of its service, p_2 .
- 3) Each consumer subscribes to one NSP or to neither.

Each NSP $i \in \{1, 2\}$ seeks to maximize its profits

$$\pi_i(p_i) = p_i N_i - c_i N_i \quad (2)$$

where N_i is the number of subscribers of NSP i and will be determined by the decisions of the consumers' decisions in the last stage of the game, and c_i is the marginal cost to the NSP of serving one subscriber. An NSP can increase its profits by

raising the price of service, but this will affect the number of subscribers it captures.

Consumers trying to maximize their individual surplus evaluate the competing services in terms of the difference in size n_i , with a larger network representing more base stations and consequently better service, as well as in terms of the difference in price p_i . We have heterogeneous consumers parameterized by taste parameter ω , which represents the degree to which the consumer values the wireless service, with ω distributed uniformly from $[0, \hat{\omega}]$. The surplus of a consumer of type ω subscribing to NSP i depends on the resource sharing scenario, the network configuration, and the relative share of base stations operated by its NSP. We use the average data rate as a metric of utility, and for mmWave networks we model it as a linear function of n_i (which we confirm empirically with the simulation in Section III), with a parameter μ capturing the network configuration.

When there is no resource sharing, the surplus of a consumer of type ω subscribing to NSP i is

$$u(\omega, n_i, p_i) = \omega \mu n_i - p_i \quad (3)$$

for $i \in \{1, 2\}$, and a consumer subscribes to at most one NSP.

If the NSPs share their mmWave network resources, then the surplus of a consumer of type ω subscribing to NSP i is

$$u\left(\omega, \sum_{k \in \{1, 2\}} n_k, p_i\right) = \omega \mu \sum_{k \in \{1, 2\}} n_k - p_i \quad (4)$$

since the quality of service of the consumer depends on the total number of base stations deployed by both NSPs.

Finally, with weighted sharing, the surplus of a consumer of type ω subscribing to NSP i is

$$u\left(\omega, \psi_i, \sum_{k \in \{1, 2\}} n_k, p_i\right) = \omega \mu \psi_i \sum_{k \in \{1, 2\}} n_k - p_i \quad (5)$$

where the utility now also depends on the weight assigned to NSP i in the scheduler, ψ_i . (We see from Figure 2a that the average user throughput for a subscriber of NSP i scales linearly with ψ_i .)

B. Solution

We can solve the simple game described above for the best response of each player, and use this to gain some insight into the market. To do so, we define two marginal consumers:

- $\underline{\omega}$ is the consumer who is indifferent between subscribing to the smaller NSP (NSP 2) or to neither.
- $\bar{\omega}$ is the consumer who is indifferent between subscribing to NSP 1 or NSP 2.

We also note that the market share of NSP 1 is

$$\frac{\hat{\omega} - \bar{\omega}}{\hat{\omega}} \quad (6)$$

and the market share of NSP 2 is

$$\frac{\bar{\omega} - \underline{\omega}}{\hat{\omega}}. \quad (7)$$

Since

$$\bar{\omega} \mu n_1 - p_1 = \bar{\omega} \mu n_2 - p_2 \quad (8)$$

and

$$\underline{\omega} \mu n_2 - p_2 = 0 \quad (9)$$

when there is no resource sharing, we find that

$$\underline{\omega} = \frac{p_2}{\mu n_2} \quad (10)$$

and

$$\bar{\omega} = \frac{p_1 - p_2}{\mu(n_1 - n_2)} \quad (11)$$

and that when $\frac{p_1}{p_2} > \frac{n_1}{n_2}$, there are positive values of p_1 , p_2 , n_1 and n_2 , where $0 \leq \underline{\omega} \leq \bar{\omega} \leq \hat{\omega}$ (i.e. both NSPs will have positive market share).

Substituting (10) and (11) into (2) and using backward induction, we find that the best responses of NSP 1 and NSP 2 are

$$p_{1,NS}^* = \frac{(2c_1 + c_2)n_1 - c_1 n_2 + 2\mu \hat{\omega} n_1 (n_1 - n_2)}{2(2n_1 - n_2)} \quad (12)$$

and

$$p_{2,NS}^* = \frac{4c_2 n_1^2 + (2c_1 - c_2 + 2\mu \hat{\omega} (n_1 - n_2))n_1 n_2 - c_1 n_2^2}{4n_1(2n_1 - n_2)} \quad (13)$$

In the equal sharing scenario, the consumer selects one NSP over the other based only on price, since it will get the benefit of all base stations by subscribing to either NSP. Therefore, the NSPs will have to compete on price in order to attract subscribers, and if either NSP sets a lower price, it will capture all of the subscribers. If both NSPs have the same marginal cost ($c_1 = c_2 = c$), then the best response is

$$p_{1,ES}^* = p_{2,ES}^* = c \quad (14)$$

and from (2) we can see that both NSPs will earn zero profit. If one NSP has a lower marginal cost, it will undercut the other (e.g. if $c_1 < c_2$, then $p_1^* = c_2 - \epsilon$) and capture all of the potential subscribers, leaving the NSP with higher marginal cost to have zero market share. Thus for this simple duopoly game, there is no way for both NSPs to earn a profit greater than zero with equal sharing.

Finally, we consider the scenario with weighted sharing. Here, since

$$\bar{\omega} \mu \psi_1 (n_1 + n_2) - p_1 = \bar{\omega} \mu \psi_2 (n_1 + n_2) - p_2 \quad (15)$$

and

$$\underline{\omega} \mu \psi_2 (n_1 + n_2) - p_2 = 0 \quad (16)$$

we find that

$$\underline{\omega} = \frac{p_2}{\mu \psi_2 (n_1 + n_2)} \quad (17)$$

$$\bar{\omega} = \frac{p_1 - p_2}{\mu (n_1 + n_2) (\psi_1 - \psi_2)} \quad (18)$$

and that when $\frac{p_1}{p_2} > \frac{\psi_1}{\psi_2}$ and $\psi_1 \geq \psi_2$, there are positive values of p_1 , p_2 , ψ_1 , ψ_2 , n_1 and n_2 , where $0 \leq \underline{\omega} \leq \bar{\omega} \leq \hat{\omega}$ (i.e. both NSPs will have positive market share).

Then, substituting (17) and (18) into (2) and using backward induction, we find that the the best response of NSP 1 is

$$p_{1,WS}^* = \frac{2\mu\hat{\omega}\psi_1(\psi_1 - \psi_2)(n_1 + n_2) + (2c_1 + c_2)\psi_1 - c_1\psi_2}{2(2\psi_1 - \psi_2)} \quad (19)$$

and the best response of NSP 2 is

$$p_{2,WS}^* = \frac{\psi_1\psi_2(2\mu\hat{\omega}(n_1+n_2)(\psi_1-\psi_2)+2c_1-c_2)+4c_2\psi_1^2-c_1\psi_2^2}{4\psi_1(2\psi_1-\psi_2)} \quad (20)$$

C. Simplified game with zero marginal costs

When $c_1 = c_2 = 0$, we show that there are conditions under which weighted sharing may be mutually beneficial for both NSPs. (Recall this in this game, there are no conditions under which both NSPs can earn profit greater than zero with *equal* sharing.)

With zero marginal costs, and when there is no resource sharing, NSP 1 earns profit

$$\pi_{1,NS} = \frac{\mu\hat{\omega}n_1(n_1 - n_2)}{2(2n_1 - n_2)} \quad (21)$$

and NSP 2 earns profit

$$\pi_{2,NS} = \frac{\mu\hat{\omega}n_1n_2(n_1 - n_2)}{4(2n_1 - n_2)^2} \quad (22)$$

With weighted sharing, NSP 1 earns profit

$$\pi_{1,WS} = \frac{\mu\hat{\omega}\psi_1(\psi_1 - \psi_2)(n_1 + n_2)}{2(2\psi_1 - \psi_2)} \quad (23)$$

and NSP 2 earns profit

$$\pi_{2,WS} = \frac{\mu\hat{\omega}\psi_1\psi_2(\psi_1 - \psi_2)(n_1 + n_2)}{4(2\psi_1 - \psi_2)^2} \quad (24)$$

We are interested in finding values of n_1 , n_2 , ψ_1 , and $\psi_2 = 1 - \psi_1$ for which weighted sharing is more profitable for both NSPs than no sharing, i.e. $\pi_{1,WS} > \pi_{1,NS}$ and $\pi_{2,WS} > \pi_{2,NS}$. For NSP 1, we find that if $\psi_1 > \frac{n_1}{n_1+n_2}$ then $\pi_{1,WS} > \pi_{1,NS}$. For NSP 2, if there exists values for n_1 , n_2 , ψ_1 , and $\psi_2 = 1 - \psi_1$ such that

$$\frac{n_1}{n_1 + n_2} < \psi_1 < \frac{4n_1^2 - 5n_1n_2 + 3n_2^2 + \sqrt{\Delta}}{4(2n_1 - n_2)^2}, \quad (25)$$

with $\Delta = 16n_1^4 - 8n_1^3n_2 - 15n_1^2n_2^2 + 10n_1n_2^3 + n_2^4$, then $\pi_{2,WS} > \pi_{2,NS}$ (and under these conditions, we also have $\pi_{1,WS} > \pi_{1,NS}$, so weighted sharing is mutually beneficial).

Figure 3 illustrates the range of n_1 and n_2 in which sharing can be mutually beneficial, i.e., where there is a positive ψ_1 and $\psi_2 = 1 - \psi_1$ such that $\pi_{1,WS} > \pi_{1,NS}$, $\pi_{2,WS} > \pi_{2,NS}$, and $n_1 + n_2 \leq 1$. In general, weighted sharing is most helpful when NSPs are similar in size. Ordinarily, similar-sized NSPs must compete on price, since there is little else to distinguish them; in a weighted sharing scenario, however, they can vary ψ_1 in order to differentiate themselves and make price competition less tough. For NSPs that are already dissimilar, the benefit of weighted sharing for easing price competition does not apply.

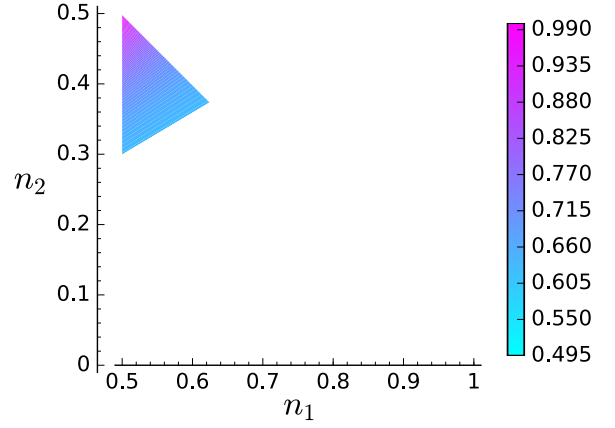


Fig. 3: The shaded region shows the values of n_1 and n_2 ($n_1 > n_2$) where there is a positive ψ_1 and $\psi_2 = 1 - \psi_1$ such that $\pi_{1,WS} > \pi_{1,NS}$, $\pi_{2,WS} > \pi_{2,NS}$, and $n_1 + n_2 \leq 1$. Furthermore, the depth of the shading gives the maximum value of ψ_1 for which this holds. The minimum value of ψ_1 for which sharing is profitable for both NSPs is $\frac{n_1}{n_1+n_2}$.

Next, we discuss the specific values of ψ_1 and $\psi_2 = 1 - \psi_1$ for which sharing is mutually beneficial. For weighted sharing to be more profitable than no sharing for NSP 1, ψ_1 should be at least $\frac{n_1}{n_1+n_2}$, i.e., the share of the airtime allocated to NSP 1 should be at least equal to its share of the resources. The maximum value of ψ_1 for which sharing is mutually beneficial is shown in Figure 3, and may be somewhat larger than $\frac{n_1}{n_1+n_2}$, especially when n_1 is not much larger than n_2 . The intuition behind this surprising result is based on the dynamics of price competition between the NSPs. The more similar the sizes of the NSPs, the tougher the price competition gets, as consumers differentiate between them mainly based on price. Thus with no sharing, similar-sized NSPs must set a low price and make little profit. With weighted sharing and large ψ_1 , however, the NSPs are differentiated in the quality of service they offer to consumers. Subject to less price competition, both NSPs can set a higher price and earn more profit than they would with no sharing, even though the quality of service offered by NSP 2 is lower with weighted sharing and large ψ_1 than with no sharing at all, as shown in Figure 2a.

Similar-sized NSPs could also be differentiated in quality by making ψ_1 small, so that the quality of NSP 2's service would be much better than NSP 1's. However, because of the greater market power afforded to NSP 1 by its position in the game, it can generally set higher prices without sharing and so it would not be more profitable with weighted sharing and $\psi_1 < \frac{n_1}{n_1+n_2}$.

The key result of this section is that *there exists* a range of market conditions (n_1 and n_2) in the duopoly game, for which weighted sharing can be more profitable than no sharing for both NSPs. Furthermore, in Section III, we have shown that weighted sharing achieves almost the full sharing gains from a purely technical perspective (in terms of network capacity). Thus, under the right market conditions, base station sharing

with a weighted scheduler may be beneficial from both a technical and economic perspective.

V. CONCLUSIONS

While resource sharing, and base station sharing in particular, can increase overall network capacity in a mmWave cellular system, NSPs may still be unwilling to share due to unfavorable competitive dynamics with equal sharing. In this work, we describe a scheduling approach with which we may:

- achieve an overall network capacity similar to an equal sharing scenario, capturing most of the potential gains due to BS diversity and multiuser diversity, and
- still maintain enough of a competitive difference between asymmetric NSPs in a duopoly market so that sharing is profitable for both.

In particular, with this approach, an NSP can achieve technical sharing gains without losing its competitive edge in the market.

We briefly discuss here some limitations of our approach. We make some approximations for tractability, such as approximating the average data rate as a linear function of the number of base stations, and approximating the average number of users in a cell as fixed in Section IV (when in fact this depends on the consumers' decisions in the game). We also use a very simple model for the game described in Section IV, although we believe this model sufficiently captures the key details of the market to support our general conclusions.

As future work, we would like to extend the model of the duopoly game in Section IV to model the dependence of consumers' decisions on the network data rate. We would also like to consider the application of our weighted sharing scheduler to other kinds of networks, such as small cell microwave networks and WiFi networks.

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