Do Open Resources Encourage Entry into the Millimeter Wave Cellular Service Market?

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ABSTRACT

The resource usage model for millimeter wave bands has been the subject of considerable debate. The massive bandwidth, highly directional antennas, high penetration loss and susceptibility to shadowing in these bands suggest certain advantages to spectrum and infrastructure sharing. In particular, resources that are "open", such as unlicensed spectrum or a deployment of base stations open to all service providers, may offer greater gains in mmWave bands than at conventional cellular frequencies. 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 network size. Detailed network simulations are used to understand data rates, profit, and demand for millimeter wave service, with and without open resources. 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.

CCS Concepts

•**Networks** → **Network economics;** *Mobile networks;*

Keywords

Cellular networks, millimeter wave, network economics

1. INTRODUCTION

The millimeter wave (mmWave) bands are the largest unlicensed bandwidths ever allocated, presenting an opportunity for technical and policy innovation. Regulatory agencies are moving quickly to open up these bands; for example, in the United States, the FCC has recently voted to open 3.85 GHz of spectrum for licensed use and 7 GHz for unlicensed use in frequencies above 24 GHz, with future plans to allocate an additional 17.7 GHz of spectrum in those bands.

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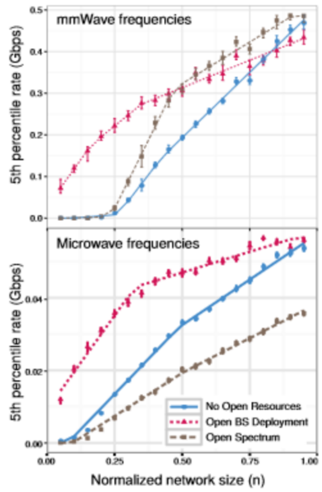
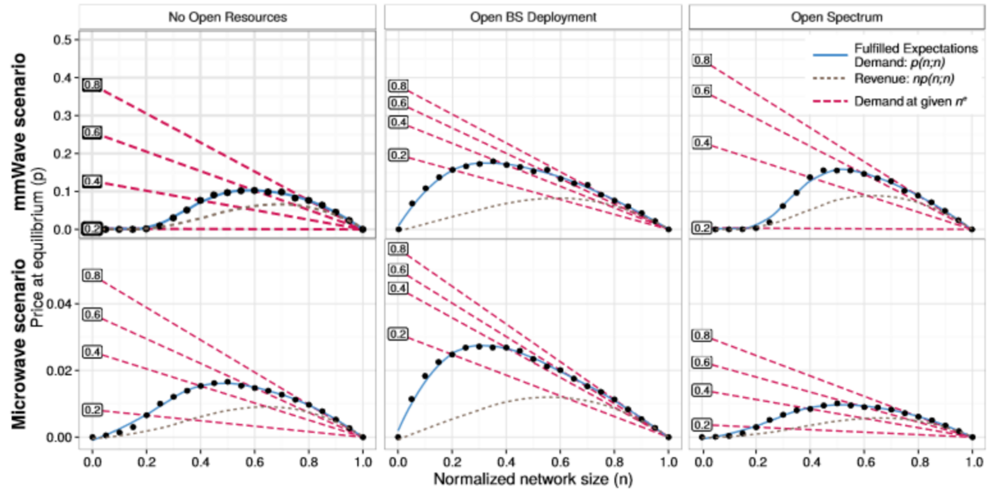
However, the specific regulatory scheme for these bands, particularly with respect to resource sharing, remains undecided. While cellular frequencies have traditionally been allocated with geographic area exclusive use licenses, technical properties of mmWave bands favor spectrum and infrastructure (base station) sharing [1, 5, 6]. In mmWave networks, 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. Also, the high penetration loss and susceptibility to shadowing suggest that many more base stations are likely to be needed for wide area coverage, motivating infrastructure sharing.

Technological justification for resource sharing, however, does not always translate to economic benefits. 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 competitor, 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. Early work in this area [1, 5, 6] generally argues for sharing, but ignores the market dynamics of demand and competition. To gain a fuller understanding of the benefits of resource sharing in mmWave networks, we need to identify the impact on quality of service, and then understand how this affects the demand, price, and cost of service.

The goal of this work is to model the strategic decisions of wireless service providers building out mmWave networks with or without open spectrum or infrastructure. We apply economic models of network goods [2] - 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 use network simulations to quantify the effect of 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* [3], 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



(a) We derive the network externalities function from the effect of increasing network size on fifth percentile rates.



(b) The demand curves for mmWave service for a range of expected network sizes n^e, fulfilled expectations demand curve where $n = n^e$, and NSP revenue. In the mmWave scenario, slow initial growth makes it difficult to reach critical mass in the case of no open resources and open spectrum, while with an open BS deployment there is robust demand and growth even at small network sizes.

utilizing an existing deployment of "open" small cells, and deploying base stations but using unlicensed "open" spectrum. We also compare the behavior of mmWave networks in this respect to that of conventional cellular networks operating at microwave frequencies.

2. NETWORK EXTERNALITIES

Consider mmWave network service as a *network good* [2], with varying demand and resources. Subscribers benefit from an indirect positive network externality: a large network service provider (NSP) with more subscribers (higher density of UEs) will build a denser deployment of base stations (BSs) and/or 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 assume that consumers decide whether or not to subscribe to a mmWave network based on its fifth percentile rates. This is supported by research which suggests that service reliability is rated highly in perceived quality of mobile services; we take fifth percentile rate as a proxy for service reliability.

Using the simulations described in [4], we find the effect of increasing network size n on fifth percentile data rates, where n is defined differently for three scenarios:

- **No open resources**: 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 (scaled to the range $[0, 1]$), but is also a scaling factor on the BS density and bandwidth of the NSP.
- **Open BS deployment**: There is a preexisting deployment of open association small cells serving all UEs, operated by a coalition of service providers or by a third party. Network size, n, refers to demand for the service and is also a scaling factor on the bandwidth of the NSP, but the BS density of the NSP is constant and equal to the size of the "open" deployment for all values of n.
- **Open spectrum**: 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. However, the bandwidth of the NSP is constant and equal to the full unlicensed bandwidth for all values of n.

The results of this simulation for both a mmWave cellular scenario and a conventional microwave cellular scenario are shown in Fig. 1(a). For both mmWave and microwave frequencies, the overall effect on fifth percentile data rates of increasing network size is piecewise linear, with the slope depending on the open resources and on whether the NSP has captured a small portion of the market (small n) or more of it (large n).

We also note some important differences between mmWave and microwave networks. First, uncoordinated spectrum sharing generally improves user rate in mmWave networks (relative to exclusive use spectrum), while in microwave networks it has the opposite effect. This is mainly due to the highly directional antennas used in the mmWave scenario. Second, in conventional microwave networks, the fifth percentile rate starts increasing even at a very small network size (small n). In mmWave networks, when there is no BS sharing, the fifth percentile rate remains flat for small n and starts increasing only at a moderate network size. This is due to the increased path loss at mmWave frequencies, where a denser deployment of BSs is necessary to prevent outage.

3. EVOLUTION OF DEMAND

Having quantified the technical effects on fifth percentile rate of increasing network size, 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 in the effect of "open" resources on new service offerings.

Using a standard utility model for network goods [2], we consider consumers whose individual utility for subscribing to mmWave network service is $u(\omega, n, p) = \omega h(n) - p$, where p is the price of service, n is the network size, and $h(n)$ is the network externalities function derived empirically from the slopes of the lines in Fig. 1(a), i.e. from the way the fifth percentile user rate changes with network size. The parameter ω is known as the *taste parameter* in economics. It is distributed uniformly on the interval $[0, 1]$ among the set of consumers, and models consumer heterogeneity.

Fig. 1(b) shows the *fulfilled expectations demand* curve for the network (constructed as described in [4]), which gives the size of the network that could be supported at equilibrium for a given price. We observe in Fig. 1(b) the initially upward-sloping fulfilled expectations demand curve that is a feature of network goods.

The slope of this curve at small network sizes is worthy of extra attention, as this determines how easily the network will reach critical mass and from there, a stable equilibrium. It is shown in [3] that under perfect competition, with marginal cost c, equilibria occur at $n = 0$ and at the two points n' and n'' where the fulfilled expectations demand curve intersects the horizontal line at $p = c$. 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 service at the lowest price at which the provider 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'' as providers try to sell the service to the part of the population with a low willingness to pay. When the fulfilled expectations demand grows quickly from $n = 0$, then n' occurs at a smaller network size, making it easier to reach critical mass and from there, the stable equilibrium at n''.

From Fig. 1(b), we find that in mmWave networks without an open deployment of BSs, the demand does not begin to grow until the network is moderately large, making it difficult for a new provider to reach critical mass. This is due to the propagation characteristics of mmWave bands, which require a denser deployment of BSs to provide coverage. With an existing deployment of "open" small cells, there is robust demand even at small network sizes, which encourages growth. Open spectrum increases demand and revenue once the network is sufficiently large, but does not have a similarly encouraging effect on market entry. In conventional microwave networks, we see the opposite: demand begins to grow even at small values of n, and unlicensed spectrum has a negative effect on demand and revenue.

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 ω will make the same choice between service providers, given their price, network size, and inherent quality. Actually, consumers are not identical in their valuations of competing services. 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 (e.g. the US fax market [3]).

4. CONCLUSIONS

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 "open" spectrum or infrastructure deployments.

Our results show that the growth of demand for mmWave service is unlike that of conventional cellular networks at microwave frequencies. We see a strong marginal network externality for small mmWave networks 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 reach a stable equilbrium and generate revenue (not considering startup costs), 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. However, this 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. Open spectrum increases demand and revenue for moderate or large-sized mmWave networks, and relies only on regulators having released the spectrum for unlicensed use in cellular systems, but does not have a similarly encouraging effect on market entry.

5. ACKNOWLEDGMENTS

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