AN ECONOMIC PERSPECTIVE ON SPECTRUM AND INFRASTRUCTURE SHARING IN MILLIMETER WAVE CELLULAR NETWORKS

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All cellular mobile communications

- 3 GHz
- 54 GHz
- 99 GHz
- 99 GHz

Potential 252 GHz available bandwidth

60 GHz oxygen absorption band

Water vapor (H₂O) absorption band

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1 Image from Khan, Pi “Millimeter Wave Mobile Broadband: Unleashing 3-300 GHz spectrum,” 2011
Technical:

- **Massive bandwidth**: FCC recently voted to open 3.85 GHz of spectrum for licensed use and 7 GHz for unlicensed use in frequencies above 24 GHz, has future plans to allocate another 17.7 GHz.
- **Directionality**: large antenna arrays, highly directional links, more spatial degrees of freedom, less interference.
- **Shadowing**: requiring a denser deployment of base stations; limited indoor penetration.
Economic, regulatory:

- **Value of spectrum**: with massive bandwidth and less interference, spectrum need not be a scarce commodity.
- **Lack of regulation**: both an opportunity and a deterrent to investment (uncertainty.)
- **Expense of deployment and operation**: denser deployments required, property rights issues, other factors.
EARLY RESEARCH CONFIRMS TECHNICAL SHARING GAINS, SUGGESTS COST SAVINGS

- “Full spectrum and infrastructure sharing configuration... results in increased user rate as well as in economical advantages for both service providers... Network providers share the infrastructure costs.”\(^2\)
- “Sharing licenses (if possible), will allow all networks to use the full spectrum simultaneously without impacting the individual achieved rates and help networks to reduce their expenses by sharing the license costs.”\(^3\)


Technical sharing gains and costs (spectrum licenses, infrastructure deployment) are only part of the picture.

- NSP may not prefer sharing if it shifts demand to a competing service provider, or if it increases price competition.
- Consumers prefer a higher quality of service, but they are also concerned with service availability and price, which could be affected by resource sharing.
How do non-exclusive resources affect markets for cellular service in mmWave bands?
HOW DO NON-EXCLUSIVE RESOURCES AFFECT MARKETS FOR CELLULAR SERVICE IN MMWAVE BANDS?

• In a market with a high-end and low-end mmWave service provider, under what conditions will sharing increase service providers’ revenue or consumer surplus?⁴

• Do open resources (unlicensed spectrum, open-association base stations) make it easier for a new mmWave cellular service provider to reach critical mass in the market?⁵


ECONOMIC FRAMEWORK: MARKETS WITH NETWORK EFFECTS
Markets for goods with network effects: where utility of consumer depends on number of units sold $n$.

Example: for consumer whose interest in the good is $\omega$,

- without network effect, reservation price $p = \omega$
- with network effect, reservation price $p = h(n)\omega$

Leads to “winner takes most” market, fierce competition for market share$^6$.

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In mmWave cellular network, supply-side network effect:

- more subscribers,
- encourages deployment of more base stations,
- and more spectrum.
TECHNICAL SYSTEM MODEL
We find $h(n)$ “empirically”, with a simulation capturing main characteristics of mmWave and small cell microwave networks:

- Channel model
- Directional transmission
• **Channel model**: empirically derived LOS, NLOS and outage channel models for mmWave links\(^7\); ITU microcell channel model for microwave links.

• **Directional transmission**: As shown.\(^8\) For mmWave frequencies we use model parameters representing an 8x8 antenna array at the base station (BS) and a 4x4 antenna array at the user equipment (UE). For microwave frequencies, we use ITU model for the BS antenna, and omnidirectional UE antenna.

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**Table 1: Network parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>mmWave</th>
<th>microwave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>73 GHz</td>
<td>2.5 GHz</td>
</tr>
<tr>
<td>Frequency reuse factor</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Network bandwidth</td>
<td>1 GHz</td>
<td>300 MHz</td>
</tr>
<tr>
<td>Network BS density</td>
<td>100 BSs/km²</td>
<td>100 BSs/km²</td>
</tr>
<tr>
<td>Network UE density</td>
<td>500 UEs/km²</td>
<td>500 UEs/km²</td>
</tr>
<tr>
<td>BS transmit power</td>
<td>30 dBm</td>
<td>30 dBm</td>
</tr>
<tr>
<td>UE noise figure</td>
<td>7 dB</td>
<td>7 dB</td>
</tr>
<tr>
<td>$(M^B, m^B, \theta^B)$</td>
<td>(20 dB, -10 dB, 5°)</td>
<td>(0 dB, -20 dB, 70°)</td>
</tr>
<tr>
<td>$(M^U, m^U, \theta^U)$</td>
<td>(10 dB, -10 dB, 30°)</td>
<td>(0 dB, 0 dB, 360°)</td>
</tr>
<tr>
<td>Rate model</td>
<td>$(1 - \alpha) W \log_2(1 + \beta \text{ SINR}), \alpha = 0.2, \beta = 0.5$</td>
<td></td>
</tr>
</tbody>
</table>
I: UNDER WHAT CONDITIONS WILL MMWAVE SERVICE PROVIDERS* WANT TO SHARE RESOURCES?
MARKET: DUOPOLY WITH VERTICAL DIFFERENTIATION

- Two service providers,
- One “high-end”, one “low-end”

(Representative of some markets in the U.S.)
Decision regarding *compatibility*:

- **Network effect**: Making a product *compatible* increases its value to consumers, if positive network externality.
- **Market power**: Making a product *compatible* increases the value of a competitors’ product and reduces the perceived difference between competing products, potentially increasing price competition and forcing prices down.
The game:

1. NSPs $i \in \{1, 2\}$ simultaneously choose quality $q_i$ from $[0, \hat{q}]$.
2. NSPs $i \in \{1, 2\}$ simultaneously set price $p_i$.
3. Each consumer subscribes to one NSP $i \in \{1, 2\}$ or neither.

Quality $q_i$ is the *inherent* quality (with maximum feasible value $\hat{q}$).

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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

$$\pi_i(q_i, n_i, p_i) = n_i p_i - q_i n_i$$

(1)
GAME: DUOPOLY WITH VERTICAL DIFFERENTIATION

Consumers parameterized by $\omega$, distributed uniformly on $[0, \hat{\omega}]$.

For consumer of type $\omega$ subscribing to NSP $i$:

$$u(\omega, q_i, \tilde{n}_i, p_i) = \omega q_i + q_i h(\tilde{n}_i) - p_i$$  \hspace{1cm} (2)

with $i \in \{1, 2\}$, $0 \leq \mu < \min[1, \hat{\omega}/2]$, and each consumer subscribes to at most one NSP.

If the NSPs share their mmWave network resources, then $\tilde{n}_i = \sum_{i \in \{1, 2\}} n_i$, otherwise $\tilde{n}_i = n_i$. 
As per simulation: the network externalities function $h(\tilde{n}_i)$ is approximately linear in $\tilde{n}_i$, and we take $h(\tilde{n}_i) = \mu \tilde{n}_i$.

The scaling factor $\mu$ determines the intensity of the network externality, and is derived from slopes of the lines as $\mu_{mm} = 0.64$ and $\mu_{micro} = 0.05$.  

GAME: DUOPOLY WITH VERTICAL DIFFERENTIATION
GAME: DUOPOLY WITH VERTICAL DIFFERENTIATION

WLOG, assign index 1 to the NSP that chooses the higher quality.

We define two marginal consumers:

• the consumer of type $\omega$ is indifferent between choosing no subscription and subscribing to NSP 2, satisfying

$$\omega q_2 + \mu q_2 \tilde{n}_2 - p_2 = 0$$  \hspace{1cm} (3)

• the consumer of type $\overline{\omega}$ is indifferent between subscribing to NSP 1 and subscribing to NSP 2, satisfying

$$\overline{\omega} q_1 + \mu q_1 \tilde{n}_1 - p_1 = \omega q_2 + \mu q_2 \tilde{n}_2 - p_2$$  \hspace{1cm} (4)

When there is one NSP (monopoly), the marginal consumer is defined by

$$\overline{\omega} q_1 + \mu q_1 \tilde{n}_1 - p_1 = 0$$  \hspace{1cm} (5)
We solve for best response of both NSPs and consumers in each market, with and without resource sharing.

We also consider sensitivity to market characteristics:

- High $\hat{q}$: more differentiation (from NSP side).
- High $\hat{\omega}$: more dispersion (from consumer side)

Both factors reduce price competition.
HIGH-END NSP HAS STRONGER INCENTIVE NOT TO SHARE IN MMWAVE NETWORKS

(a) ($\hat{q} = 1$) In mmWave network, low-end NSP has stronger desire to share but high-end NSP has stronger desire not to (compared to equivalent market for microwave service).

(b) ($\hat{q} = 1.5$) In a market with high potential for quality differentiation, there is less price competition and it is possible for both NSPs to prefer sharing (but less than they would in equivalent microwave market).
CONSUMER SURPLUS IS GREATER WITH SHARING ONLY IN CIRCUMSTANCES WHEN NSP PROFIT IS NOT

(a) ($\hat{q} = 1$) Consumers prefer resource sharing in mmWave networks, partly because it drives down price of the high-end option. In this market, sharing is not desirable to high-end NSP.

(b) ($\hat{q} = 1.5$) In a market with high potential for quality differentiation, there is less price competition, so both NSPs prefer sharing... but consumers don’t, because prices will be higher.
WITH RESOURCE SHARING, SOME SUBSCRIBERS WILL SWITCH FROM HIGH-END TO LOW-END NSP

(a) ($\hat{q} = 1$) Resource sharing can increase total market coverage by making the low-end NSP’s service more valuable. But, this occurs in a market where the high-end NSP prefers not to share.

(b) ($\hat{q} = 1.5$) In a market where sharing may be profitable for both NSPs, it does not increase total coverage, but shifts subscribers from high-end to low-end NSP - probably still undesirable to high-end NSP.
• The competitive advantage held by the high-end NSP due to *not* sharing resources is greater in mmWave market than in microwave market.

• Sharing is profitable for the high-end NSP only when there is great potential for quality differentiation, and therefore, little price competition.
CONCLUSIONS (2): UNDER WHAT CONDITIONS WILL MMWAVE SERVICE PROVIDERS SHARE RESOURCES?

- Under those conditions, consumers do not favor sharing because of high prices.
- Even in a market where sharing seems profitable to high-end NSP, it loses subscribers to the low-end NSP, which may be undesirable to high-end NSP due to factors not captured in our model.
Regulators may still consider mandated sharing under circumstances where, due to factors not captured in this model, the low-end NSP would choose to leave the market. In this case, mandated sharing increases the low-end NSP’s profits and might encourage it to stay in the market, improving consumer surplus relative to a monopoly.
II: DO OPEN RESOURCES MAKE IT EASIER TO REACH CRITICAL MASS?
Market with perfect competition,

- Large number of service providers,
- besides for network size, consumers have no preference for one vs. another.
REACHING CRITICAL MASS

The graph illustrates the relationship between network size (n) and price (p), showing how the price decreases as the network size increases. The critical mass is reached when the price drops below a certain threshold, indicated by the points n' and n''. This concept is crucial in understanding market dynamics and consumer behavior.
Before offering service in a given market, service providers build out a network. How big does this network have to be?

Do open resources make it easier?
ESTIMATE CONSUMER UTILITY AT DIFFERENT STAGES OF DEPLOYMENT (OR, DIFFERENT NETWORK SIZES)

No open resources: An NSP scales its spectrum and BSs according to the number of subscribers it has.

Open BS deployment: Network size, $n_i$, 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 $n_i$.

Open spectrum: Here, $n_i$ 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 $n_i$.

mmWave network

- Open base stations are most helpful in a small network, when coverage is the greatest challenge.
- Open spectrum doesn't help outage-limited users, but has a strong positive effect on users with high SINR. (Interference is negligible.)
Compared to microwave networks, mmwave networks have very different growth dynamics.

In microwave networks, open resources help for all network sizes.

Open spectrum doesn't help outage-limited users, but has a strong positive effect on users with high SINR. (Interference is negligible.)

Open base stations are most helpful in a small network, when coverage is the greatest challenge.
In mmWave networks, slow initial growth makes it difficult to reach critical mass.

With open base stations: robust demand and growth even at small network sizes.

Microwave networks have small-network demand that is more favorable to providers.
CONCLUSIONS: DO OPEN RESOURCES MAKE IT EASIER TO REACH CRITICAL MASS?

- Without open base stations, a mmWave cellular provider has to deploy enough base stations for a moderately sized network even if it has a very small number of subscribers.
- Open base stations make it easier to reach critical mass, so they may be helpful for encouraging market entry.
- Open spectrum does not improve performance for small network sizes, so it does not have as encouraging an effect on market entry.
FOR FURTHER DETAILS:


Questions