# To Help or Disturb: Introduction of Crowdsourced WiFi to 5G Networks

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Pillar of Engineering Systems and Design
Singapore University of Technology and Design (SUTD)

September 12, 2023

SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN

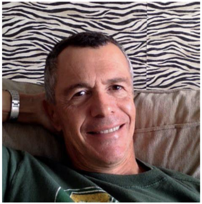
# About SUTD

- A new public university established in 2009.
- Was established in collaboration with MIT.
- Ranking in the world: 21st in Telecommunication Engineering according to ShanghaiRanking 2023.

# Acknowledgement

- This is a joint work with Associate Professor Lingjie Duan.

Prof. Lingjie Duan



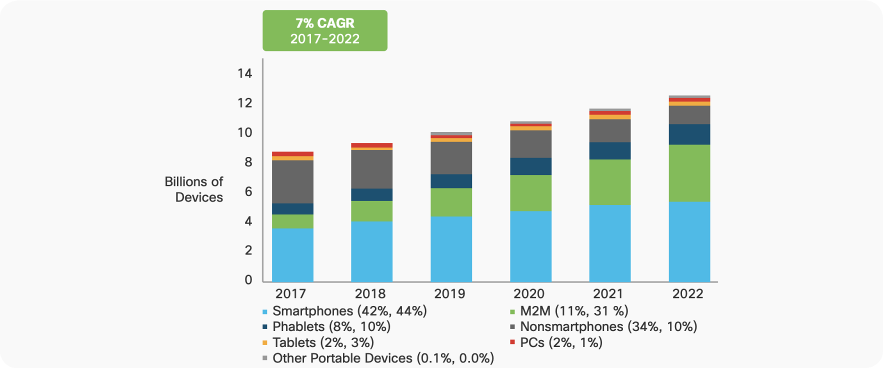
Prof. Costas Courcoubetis

- Results here have been appeared in IEEE TMC.
- **Shugang Hao** and Lingjie Duan, "To Help or Disturb: Introduction of Crowdsourced WiFi to 5G Networks," IEEE Transactions on Mobile Computing (**IEEE TMC**), vol. 22, no. 9, pp. 5583-5596, 1 Sept. 2023.

# Overview

# Background: Overwhelming Mobile Devices

**Figure 4.** Global Mobile Devices and Connections Growth




Note: Figures in parentheses refer to 2017, 2022 device share.
Source: Cisco VNI Mobile, 2019.

Rapid proliferation of mobile devices.

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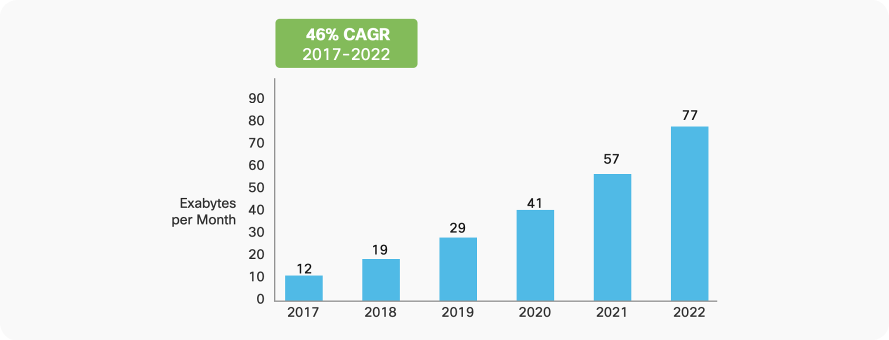
Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022, 2019, [online] http://media.mediapost.com/uploads/CiscoForecast.pdf

# Background: Overwhelming Mobile Data Traffic

**Figure 2.** Cisco Forecasts 77 Exabytes per Month of Mobile Data Traffic by 2022




Source: Cisco VNI Mobile, 2019

Mobile data traffic has been ever-increasing overwhelmingly with rapid proliferation of mobile devices.

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# Background: Profile Wireless Technology Issues

To meet overwhelming data traffic demand,

[1] GSMA, "Estimating the mid-band spectrum needs in the 2025-2030 time frame," Jul. 2021, [online] Available: https://www.gsma.com/spectrum/wp-content/uploads/2021/07/Estimating-Mid-Band-Spectrum-Needs.pdf.

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  - It is difficult to deploy a ubiquitous WiFi network[2].

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BT Fon WiFi Map, https://www.btwifi.co.uk/find/.

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Fon's crowdsourced WiFi network

- has included over 23 million APs,
- and is fast expanding to cover many populous and crowded places.


WiFi hotspots by Fon in London area.

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# Background: WiFi's Complementary for 5G

The crowdsourced WiFi community network's coverage

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Co-existing 5G and crowdsourced WiFi networks:

+ British Telecom and Fon in the United Kingdom,
– Telenor and OpenSpark in Finland.

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Features of 5G and crowdsourced WiFi networks:

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| Coverage | Ubiquitous | Limited |
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WiFi's complementarity for 5G:

5G users may add on the crowdsourced WiFi.

# Research Questions

We will answer, after the introduction of the crowdsourced WiFi network,

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**will 5G operator gain more?**

**how will users' payoffs change?**

# Related Work on Traffic Offloading

Li et al. (2019), Iosifidis et al. (2015), Lee et al. (2014)

- assumed a cellular network operator's deploying his own WiFi network to offload data traffic,
- focused on central operation.

Manshaei et al. (2008), Li et al. (2021)

- ignored the negative network externalities of the 5G network due to congestion.

Gao et al. (2014)

- only studied how a 5G operator bargains with a traditional WiFi network to decide the offloaded traffic amount and associated payment,
- ignored the crowdsouced WiFi's positive network externality and the users' choices on both service.

# Related Work on Network Externalities

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- WiFi's complementarity for 5G networks.
- Positive & negative network externalities in crowdsourced WiFi.
- Negative network externalities in 5G network due to congestion.

# References


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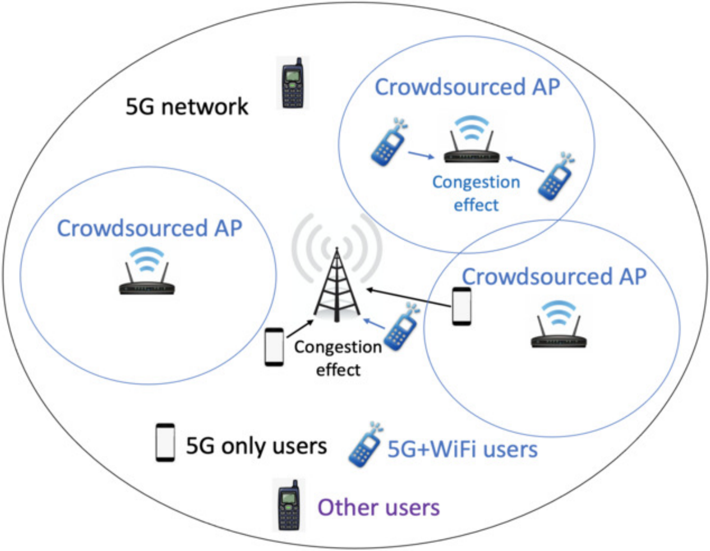
# System Model




Co-existence of the 5G and the crowdsourced WiFi networks.

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5G operator's profit is a product of the number of subscribers and the price per subscriber:

$$\bar{\pi}_1(\bar{p}_1) = N \cdot \bar{x}_1(\bar{p}_1) \cdot \bar{p}_1,$$

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Users have different sensitivities to the 5G congestion:

- the 5G operator only knows that each user's sensitivity $\theta \in [0, 1]$ follows continuous cumulative distribution function (CDF) $F(\cdot)$.

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The user's payoff of 5G subscription is given by:

$$\bar{u}_1(\theta) = V_1 - \frac{N\bar{x}_1}{Q}\theta - \bar{p}_1.$$

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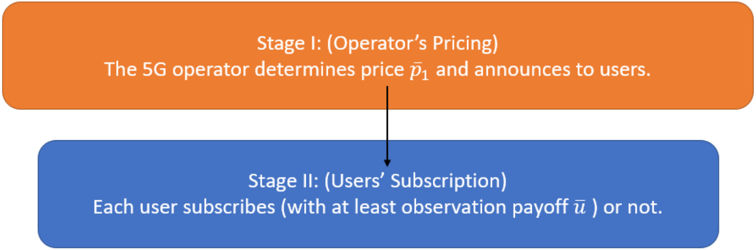
# Two-stage Stackelberg Game

In practice, the network operators have more power to lead as compared to the users as followers.



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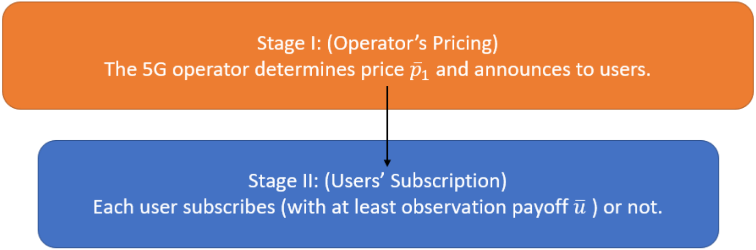


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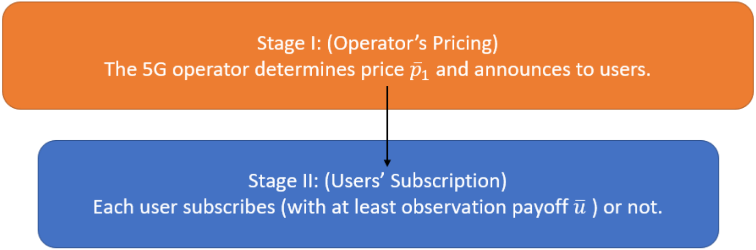



We expect all users' subscription with non-small capacity.

We will derive equilibrium with backward induction.

# Users' Equilibrium Participation in Stage II

Denote $F^{-1}(\cdot)$ as the inverse function of CDF of users' congestion sensitivity $F(\cdot)$.

Only users of low 5G congestion sensitivity will join the 5G network.

We expect the marginal user's payoff is equal to the fixed reservation payoff.

$$\bar{u}_1(\theta = F^{-1}(\bar{x}_1^*)) = \bar{u}.$$

# Users' Equilibrium Participation in Stage II

**Lemma 1. Equilibrium in Stage II before the introduction of the crowdsourced WiFi**

Given any 5G price $\bar{p}_1$ in Stage I, only users with low congestion sensitivity $\theta \leq F^{-1}(\bar{x}_1^*)$ decide to join the 5G network, where

$$\bar{x}_1^* = \begin{cases} 1, & \text{if } \bar{p}_1 \leq V_1 - \bar{u} - N/Q, \\ F(\bar{\theta}^*), & \text{if } V_1 - \bar{u} - N/Q < \bar{p}_1 < V_1 - \bar{u}, \\ 0, & \text{if } \bar{p}_1 \geq V_1 - \bar{u}, \end{cases}$$

and cutoff $\bar{\theta}^* \in (0, 1)$ is the unique solution to

$$V_1 - \frac{N}{Q} F(\bar{\theta}^*)\bar{\theta}^* - \bar{p}_1 - \bar{u} = 0.$$

The final 5G subscription fraction $\bar{x}_1^*$ increases with the 5G network capacity $Q$ and decreases with price $\bar{p}_1$.

# 5G Operator's Equilibrium Pricing in Stage I

Now we turn to Stage I to find 5G's best pricing.

With Stage II's user subscription $\bar{x}_1^*$, the 5G profit objective becomes

$$\bar{\pi}_1 = \begin{cases} N\bar{p}_1, & \text{if } \bar{p}_1 \le V_1 - \bar{u} - N/Q, \\ N\bar{p}_1 F(\bar{\theta}^*), & \text{if } V_1 - \bar{u} - N/Q < \bar{p}_1 < V_1 - \bar{u}, \\ 0, & \text{if } \bar{p}_1 \ge V_1 - \bar{u}. \end{cases}$$

The problem is still non-convex and is difficult to solve analytically given general $F(\theta)$ distribution.

# 5G Operator's Equilibrium Pricing in Stage I

## Proposition 1. Stage I's Equilibrium before the introduction of crowdsourced WiFi

Assume PDF $f(\theta)$ of users' congestion sensitivity is continuous and non-increasing, which applies to uniform, exponential and Pareto distributions. At the equilibrium of the Stackelberg game, the 5G price equilibrium in Stage I is:

$$\bar{p}_1^* = \begin{cases} V_1 - \bar{u} - \frac{N}{Q}\bar{\theta}^* F(\bar{\theta}^*), & \text{if } Q < \left(2 + \frac{1}{f(1)}\right)\frac{N}{V_1 - \bar{u}}, \\ V_1 - \bar{u} - \frac{N}{Q}, & \text{if } Q \geq \left(2 + \frac{1}{f(1)}\right)\frac{N}{V_1 - \bar{u}}, \end{cases}$$

and the fraction of 5G subscribers $\bar{x}_1^*$ is:

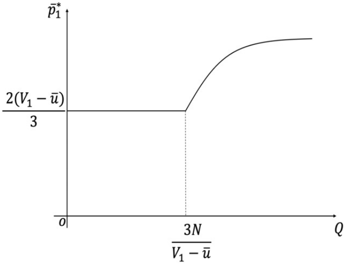
$$\bar{x}_1^* = \begin{cases} F(\bar{\theta}^*), & \text{if } Q < \left(2 + \frac{1}{f(1)}\right)\frac{N}{V_1 - \bar{u}}, \\ 1, & \text{if } Q \geq \left(2 + \frac{1}{f(1)}\right)\frac{N}{V_1 - \bar{u}}, \end{cases}$$

where $\bar{\theta}^* \in (0, 1)$ is the solution to

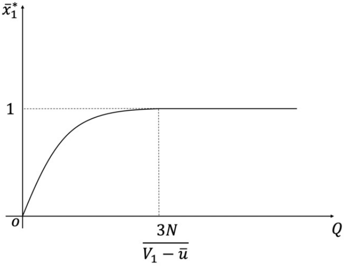
$$f(\bar{\theta}^*)\left(V_1 - \bar{u} - \frac{2N}{Q}F(\bar{\theta}^*)\bar{\theta}^*\right) - \frac{N}{Q}F^2(\bar{\theta}^*) = 0.$$

# Equilibrium of Two-stage Stackelberg Game

With users' congestion sensitivity $\theta \sim U[0,1]$, we have equlibrium as follows.




(a) 5G price equilibrium $\bar{p}_1^*$ versus the 5G network capacity $Q$




(b) Users' subscription $\bar{x}_1^*$ versus capacity $Q$

- The 5G operator can only charge a small price when capacity is low.
- Having non-small $Q$, his price increases.

# System Model after the Introduction of the Crowdsourced WiFi

After the introduction of the crowdsourced WiFi,

- 5G users can further add on the crowdsourced WiFi service.

Mohammad Hossein Manshaei, et al., "On wireless social community networks," in Proc. IEEE INFOCOM, 2008.

# System Model after the Introduction of the Crowdsourced WiFi

After the introduction of the crowdsourced WiFi,

- 5G users can further add on the crowdsourced WiFi service.
- $x_1 \in [0, 1]$: the fraction of $N$ users joining the 5G network only,
- $x_2 \in [0, 1]$: the fraction of joining both 5G+WiFi.

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Each 5G+WiFi user

- contributes a normalized positive addition $\alpha \in (0, 1)$ to the network coverage (using his home AP),
- the overall coverage of the crowdsourced WiFi network is $\alpha x_2$.

Mohammad Hossein Manshaei, et al., "On wireless social community networks," in Proc. IEEE INFOCOM, 2008.

# System Model after the Introduction of the Crowdsourced WiFi

Now the fraction $x_2$ in the crowdsourced WiFi also affects the 5G congestion.

Each 5G+WiFi user finds himself

- in the WiFi coverage with probability $\alpha x_2$,
- and outside with probability $1 - \alpha x_2$.

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$x_1 + x_2(1 - \alpha x_2)$ fraction of users will share the limited capacity $Q$.

# A 5G-only User's Payoff after the Introduction of the Crowdsourced WiFi

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The user's payoff of 5G subscription only is

$$u_1(\theta) = V_1 - \frac{N(x_1 + x_2(1 - \alpha x_2))}{Q}\theta - p_1.$$

# A 5G+WiFi User's Payoff after the Introduction of the Crowdsourced WiFi

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The user's payoff of 5G+WiFi subscription is

$$u_2(\theta) = (1 - \alpha x_2) V_1 + \alpha x_2 V_2 - (1 - \alpha x_2) \frac{N(x_1 + x_2(1 - \alpha x_2))}{Q} \theta - p_1 - p_2.$$

We will give analysis on WiFi congestion later to show similar insights.

# Operators' Profits after the Introduction of the Crowdsourced WiFi

Both $x_1$ and $x_2$ fractions of users pay the 5G operator with price $p_1$, the 5G operator's profit changes to:

$$\pi_1 = N(x_1 + x_2)p_1,$$

Li et al., "Optimal Pricing for Peer-to-Peer Sharing With Network Externalities," in IEEE/ACM Transactions on Networking, vol. 29, no. 1, pp. 148-161, 2021.

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The crowdsourced WiFi operator selfishly decides price $p_2$ to the fraction $x_2$ of users, and his profit is:

$$\pi_2 = Nx_2(p_2 - c),$$

$c$: the deployment cost per user/AP.

Li et al., "Optimal Pricing for Peer-to-Peer Sharing With Network Externalities," in IEEE/ACM Transactions on Networking, vol. 29, no. 1, pp. 148-161, 2021.

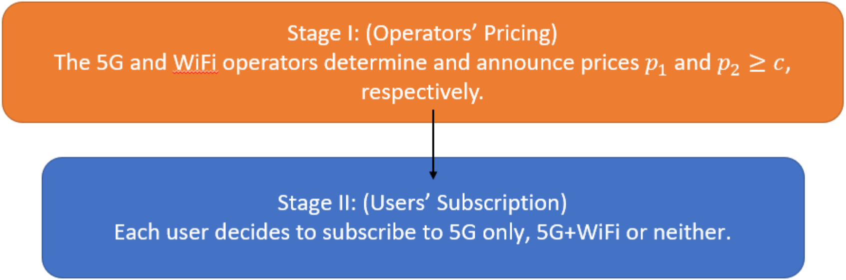
# Two-stage Dynamic Game

Stage I: (Operators' Pricing)
The 5G and WiFi operators determine and announce prices $p_1$ and $p_2 \geq c$, respectively.

↓

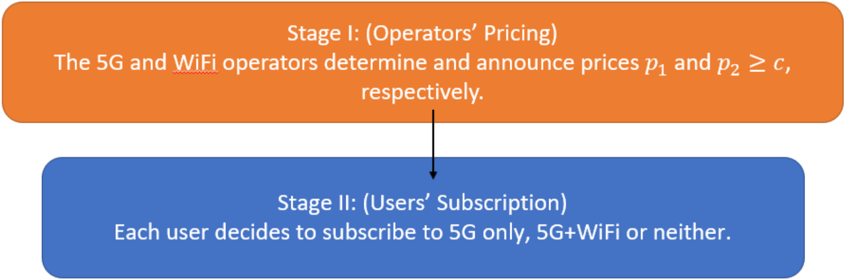
Stage II: (Users' Subscription)
Each user decides to subscribe to 5G only, 5G+WiFi or neither.

# Two-stage Dynamic Game




We expect more users' subscription after the introduction of the crowdsourced WiFi.

# Two-stage Dynamic Game




We expect more users' subscription after the introduction of the crowdsourced WiFi.

We will derive equilibrium with backward induction.

# Equilibrium Analysis in Stage II

The analysis of a user's decision is involved:

- a user to add on WiFi helps reduce the 5G users' congestion and improve the WiFi network coverage.

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- we first suppose the equilibrium fractions of users in 5G and 5G+WiFi (i.e., $x_1^*$ and $x_2^*$) are known and stable,

# Equilibrium Analysis in Stage II

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To simplify the user choice analysis:

- we first suppose the equilibrium fractions of users in 5G and 5G+WiFi (i.e., $x_1^*$ and $x_2^*$) are known and stable,
- and derive each user's choice according to his personalized cost congestion $\theta$.

# Users' Subscription in Stage II

**Lemma 2. Stage II's equilibrium after the introduction of the crowdsourced WiFi**

At the equilibrium of Stage II, a user decides his service choice by comparing his personalized congestion cost $\theta \in [0,1]$ to two cutoff points $F^{-1}(x_1^*)$ and $F^{-1}(x_1^* + x_2^*)$ as in the following two cases.

- If there are a positive number of subscribers to choose 5G+WiFi (i.e., $x_2^* > 0$), a user's equilibrium choice is:

$$\phi(\theta) = \begin{cases} 1 \text{ (5G only)}, & \text{if } \theta \leq F^{-1}(x_1^*) \text{ and } u_1(\theta) \geq \bar{u}, \\ 2 \text{ (5G+WiFi)}, & \text{if } \theta \in (F^{-1}(x_1^*), F^{-1}(x_1^* + x_2^*)] \text{ and } u_2(\theta) \geq \bar{u}, \\ 0 \text{ (Neither)}, & \text{if } \theta \in (F^{-1}(x_1^* + x_2^*), 1], u_1(\theta) < \bar{u}, \text{ and } u_2(\theta) < \bar{u}. \end{cases}$$

- If there is no subscriber to 5G+WiFi (i.e., $x_2^* = 0$), a user's equilibrium choice is:

$$\phi(\theta) = \begin{cases} 1, \text{ if } \theta \leq F^{-1}(x_1^*) \text{ and } u_1(\theta) \geq \bar{u}, \\ 0, \text{ if } \theta \in (F^{-1}(x_1^*), 1], u_1(\theta) < \bar{u}, \text{ and } u_2(\theta) < \bar{u}. \end{cases}$$

# Users' Subscription in Stage II

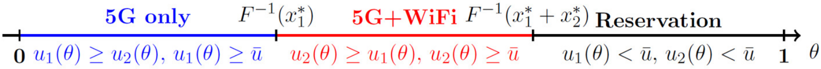



Fig. 3(a)

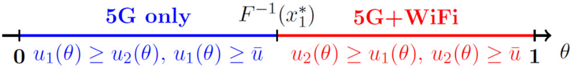



Fig. 3(b)

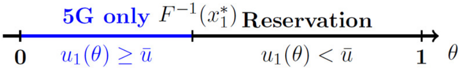



Fig. 3(c)

- Congestion-insensitive users join 5G only to avoid additional payment.
- Congestion-sensitive users may join 5G+WiFi for better experience.

# Equilibrium in Stage II

**Proposition 2.**

At the equilibrium of Stage II, user fraction of the 5G and WiFi networks (i.e., $x_1^*$ and $x_2^*$) are solutions to

$$u_1(F^{-1}(x_1^*)) = u_2(F^{-1}(x_1^*)), \;\; u_2(F^{-1}(x_1^* + x_2^*)) = \bar{u},$$

if $x_1^* + x_2^* < 1$, and otherwise

$$u_1(F^{-1}(x_1^*)) = u_2(F^{-1}(x_1^*)), \;\; x_1^* + x_2^* = 1,$$

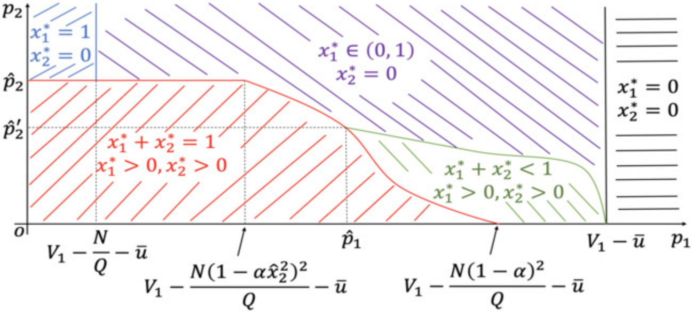
with $u_2(F^{-1}(x_1^* + x_2^*)) \geq \bar{u}$, where $x_2^* \in (0, 1)$ is the largest among all the possible solutions.

# Equilibrium in Stage II

To deliver clean engineering insights, We consider

- users obtain the same mobile access profits as $V_1 = V_2$,
- users' congestion sensitivity to follow the uniform distribution: $\theta \sim U[0, 1]$.

Later we will show similar insights with $\theta$'s truncated normal distribution.




If both prices of the 5G and the add-on WiFi services are low (see the lower left region), all the users either choose 5G or 5G+WiFi service.

# Equilibrium in Stage II

## Proposition 2. Stage II's equilibrium

The previous figure summarizes the structural results of the Stage II's equilibrium ($x_1^*$, $x_2^*$) in five cases, as functions of any given prices $p_1$ and $p_2$. For example, if both prices of the 5G and the add-on WiFi services are low (see the lower left region), i.e.,

$$p_1 \leq V_1 - \bar{u} - \frac{N}{Q}, \;\; p_2 \leq \alpha \hat{x}_2 \frac{N}{Q}\left(1 - \alpha \hat{x}_2^2\right)\left(1 - \hat{x}_2\right),$$

with $\hat{x}_2 \in [0, 1]$ as the unique solution to

$$4\alpha \hat{x}_2^3 - 3\alpha \hat{x}_2^2 - 2\hat{x}_2 + 1 = 0,$$

then all the users either choose 5G or 5G+WiFi service without leaving the wireless market (i.e., $x_1^* + x_2^* = 1$), and the equilibrium user fraction $x_2^*$ of 5G+WiFi is the greatest root in the range (0,1) to

$$p_2 - \alpha x_2^* \frac{N}{Q}\left(1 - \alpha (x_2^*)^2\right)\left(1 - x_2^*\right) = 0.$$

In another region (in the lower mid region), where the 5G capacity is small (i.e, $Q < \frac{N}{V_1 - \bar{u}}$) and the WiFi coverage addition per AP is small (i.e., $\alpha < 1 - \sqrt{\frac{V_1 - \bar{u}}{N/Q}}$), at the equilibrium not all the users choose 5G or 5G+WiFi service (i.e., $x_1^* + x_2^* < 1$).

# Equilibrium Analysis in Stage I

We do not have closed-form solutions of $x_1^*$ and $x_2^*$ in Stage II,

- it is even more difficult to derive the profit objectives $\pi_1$ and $\pi_2$.

To make it tractable on 5G profits:

- we first keep the 5G operator's price unchanged after the introduction of the crowdsourced WiFi,
- and we will prove that the 5G operator can still gain from the introduction of the crowdsourced WiFi.

# 5G Operator's Equilibrium Profit in Stage I

**Lemma 3.**

At the equilibrium of the whole dynamic game, the 5G operator obtains at least the same profit after the introduction of the crowdsourced WiFi, i.e., $\pi_1^* \geq \bar{\pi}_1^*$.

**Proposition 4. More profit with non-large capacity regime**

At the equilibrium of the whole dynamic game, the 5G operator obtains a strictly greater profit after the introduction of the crowdsourced WiFi, i.e., $\pi_1^* > \bar{\pi}_1^*$, as long as the 5G capacity is small (i.e., $Q < 3N/(V_1 - \bar{u})$) and WiFi deployment cost is small.

**Proposition 6. More profit with large capacity regime**

At the equilibrium of the whole dynamic game, the 5G operator obtains a strictly greater profit after the introduction of the crowdsourced WiFi, i.e., $\pi_1^* > \bar{\pi}_1^*$, as long as the WiFi deployment cost is small as in Proposition 5, and the 5G network capacity is large (i.e., $Q \geq 3N/(V_1 - \bar{u})$).

# 5G Operator's Pricing in Large Capacity Regime

## Proposition 5.

At the equilibrium, the 5G network operator charges at least the same 5G price (i.e., $p_1^* \geq \bar{p}_1^*$ if the 5G capacity is non-small (i.e., $Q \geq 3N/V_1$). Furthermore, the 5G operator charges a strictly greater price (i.e., $p_1^* > \bar{p}_1^*$) if the 5G capacity is non-small (i.e., $Q \geq 3N/V_1$) and deployment cost per AP is small, that is,

$$c \leq \alpha \hat{x}_2 \frac{N}{Q}(1 - \alpha \hat{x}_2^2)(1 - \hat{x}_2),$$

with $\hat{x}_2 \in (0, 1)$ as the unique solution to

$$4\alpha \hat{x}_2^3 - 3\alpha \hat{x}_2^2 - 2\hat{x}_2 + 1 = 0.$$

# 5G Operator's Pricing in Medium Capacity Regime

## Proposition 7.

At the equilibrium, the 5G operator charges users more (i.e., $p_1^* > \bar{p}_1^*$) after the introduction of the crowdsourced WiFi if the 5G network capacity is small (i.e., $3(\frac{\sqrt{17}+23}{32})^2 N/V_1 < Q < 3N/V_1$), the WiFi coverage addition per AP is non-small, that is,

$$\alpha \geq \left( \frac{2\sqrt{1-\sqrt{\frac{V_1}{3N/Q}}}\left(1-2\sqrt{\frac{V_1}{3N/Q}}\right)}{2-3\sqrt{\frac{V_1}{3N/Q}}} \right)^2,$$

and deployment cost per user $c$ is small, that is,

$$c \leq \alpha \hat{x}_2 \frac{N}{Q}(1-\alpha \hat{x}_2^2)(1-\hat{x}_2),$$

with $\hat{x}_2 \in (0,1)$ as the unique solution to

$$4\alpha \hat{x}_2^3 - 3\alpha \hat{x}_2^2 - 2\hat{x}_2 + 1 = 0.$$

# 5G Operator's Pricing in Small Capacity Regime

## Proposition 8.

At the equilibrium, the 5G operator charges users less (i.e., $p_1^* < \bar{p}_1^*$) after the introduction of the crowdsourced WiFi if the following conditions hold:

- the 5G network capacity is small (i.e., $Q < N/V_1$),
- the WiFi coverage addition per AP is small (i.e., $\alpha < 1 - \sqrt{\frac{V_1}{N/Q}}$),
- deployment cost per user $c$ is non-small as

$$c \in \Bigg( \frac{1-\sqrt{1-3\alpha\sqrt{\frac{V_1}{3N/Q}}}}{3} \frac{N}{Q}\sqrt{\frac{V_1}{3N/Q}}\Bigg(\sqrt{\frac{V_1}{3N/Q}} - \frac{1-\sqrt{1-3\alpha\sqrt{\frac{V_1}{3N/Q}}}}{3\alpha}\Big(1-\frac{1-\sqrt{1-3\alpha\sqrt{\frac{V_1}{3N/Q}}}}{3}\Big)\Bigg),$$

$$\frac{1-\sqrt{1-3\alpha\sqrt{\frac{V_1}{N/Q}}}}{3} \frac{N}{Q}\sqrt{\frac{V_1}{N/Q}}\Bigg(\sqrt{\frac{V_1}{N/Q}} - \frac{1-\sqrt{1-3\alpha\sqrt{\frac{V_1}{N/Q}}}}{3\alpha}\Big(1-\frac{1-\sqrt{1-3\alpha\sqrt{\frac{V_1}{N/Q}}}}{3}\Big)\Bigg)\Bigg).$$

# Users' Less Payoffs at the Equilibrium

**Proposition 9.**

At the equilibrium, all the users obtain strictly less payoff after the introduction of the crowdsourced WiFi (i.e, $\max\{u_1^*(\theta), u_2^*(\theta)\} < \bar{u}_1^*(\theta)$), if the 5G capacity is non-small (i.e., $Q \geq 3N/V_1$) and deployment cost per AP is small, that is,

$$c \leq \alpha \hat{x}_2 \frac{N}{Q}(1 - \alpha \hat{x}_2^2)(1 - \hat{x}_2),$$

with $\hat{x}_2 \in (0, 1)$ as the unique solution to

$$4\alpha \hat{x}_2^3 - 3\alpha \hat{x}_2^2 - 2\hat{x}_2 + 1 = 0.$$

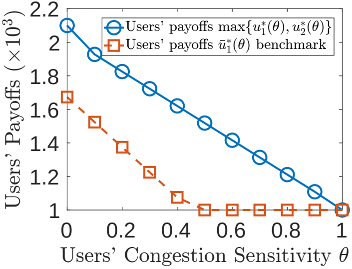
- Users obtain less with higher price after the introduction of the crowdsourced WiFi.

# Numerical Results

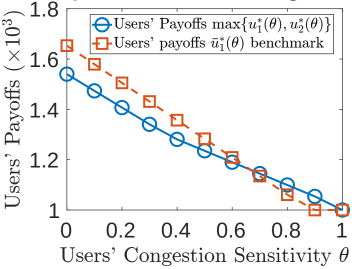
- We consider $\theta$'s truncated normal distribution to numerically show similar insights.
- The WiFi deployment cost per access point includes the special router cost in tens or hundreds of dollars: $c = 100$ and 50.
- We refer the 5G operator's prices as users' annual payment to network operators, ranging from hundreds to thousands of dollars.

AT&T's 5G plan, https://www.att.com/plans/unlimited-data-plans/.

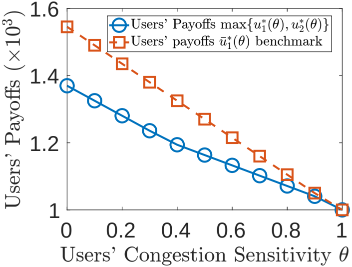
# Numerical Results on Users' Equilibrium Payoffs




(c) Small Capacity $Q = 30$

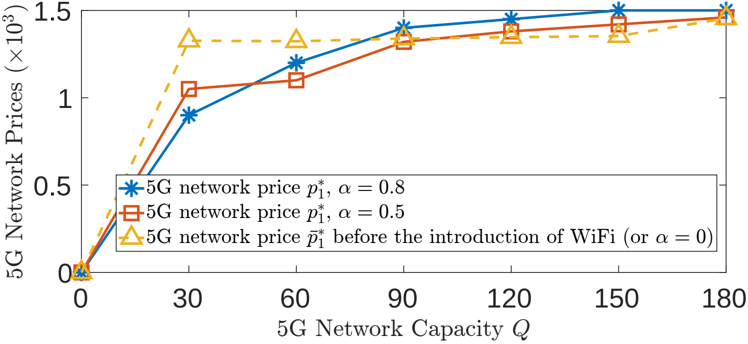



(d) Small Capacity $Q = 120$



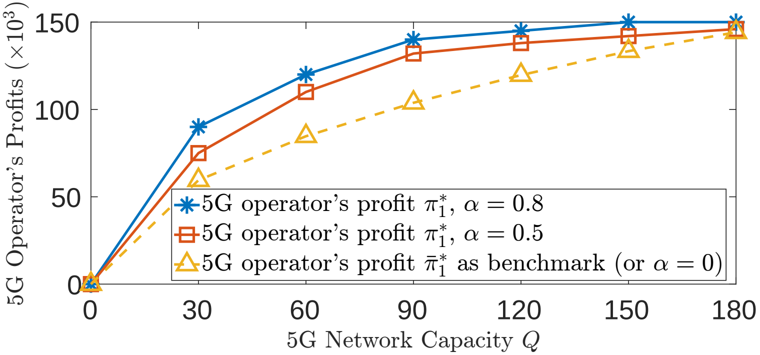

(e) Non-small capacity $Q = 180$

# Numerical Results on 5G's Pricing




Small 5G network capacity $Q$=30,
decreased 5G price with increased AP coverage $\alpha$.

# Numerical Results on 5G's Profits




Non-small 5G capacity brings less improvement on 5G profit after the introduction of the crowdsourced WiFi.

# Extension to Congested WiFi Case

We suppose $V_1 = V_2 = V$ for ease of exposition.

After we consider WiFi congestion,

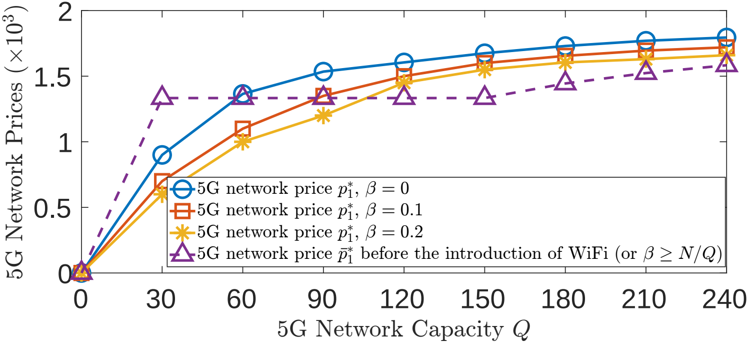
- a 5G-only user's payoff does not change,
- a 5G+WiFi user's becomes

$$\tilde{u}_2(\theta) = V - (1 - \alpha x_2)\frac{N(x_1 + x_2(1 - \alpha x_2))}{Q}\theta - \alpha x_2 \beta\theta - p_1 - p_2.$$

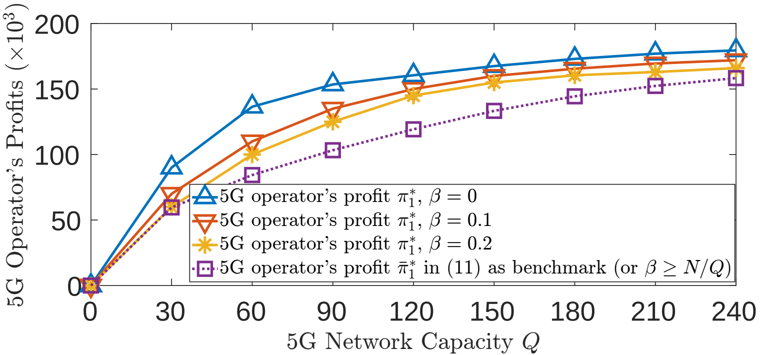
Users' subscription behaviors are the same.

5G operator obtains more after the introduction.

# Numerical Results on 5G's Pricing



# Numerical Results on 5G's Profits



# Summary

We considered

- WiFi's complementarity for 5G networks.
- Both incur diverse network externalities.

We showed that after the introduction of the crowdsourced WiFi,

- 5G operator obtains more profit,
- 5G's structural pricing,
- all the users' payoffs may be worse.

We extended to congested WiFi with similar insights.

# Thank You! Q & A