THE IMPACT OF SMALL-CELL BANDWIDTH REQUIREMENTS ON STRATEGIC OPERATORS

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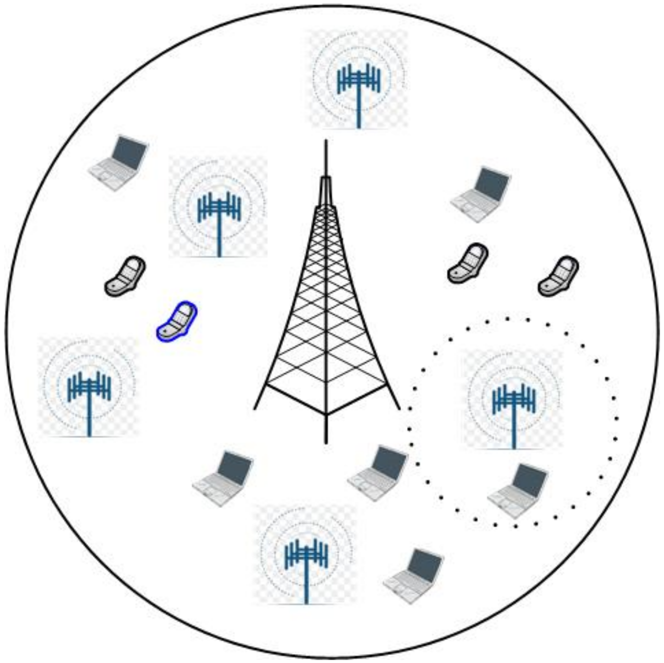
5G Trends

- Heterogeneous networks
  - Cells (Macro/Small)
- Heterogeneous services
  - Mobility, Quality of Experience

How does policy influence the strategic behavior of the service providers?

- Pricing
- Resource allocation (macro vs. micro)



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  - Cells (Macro/Small)
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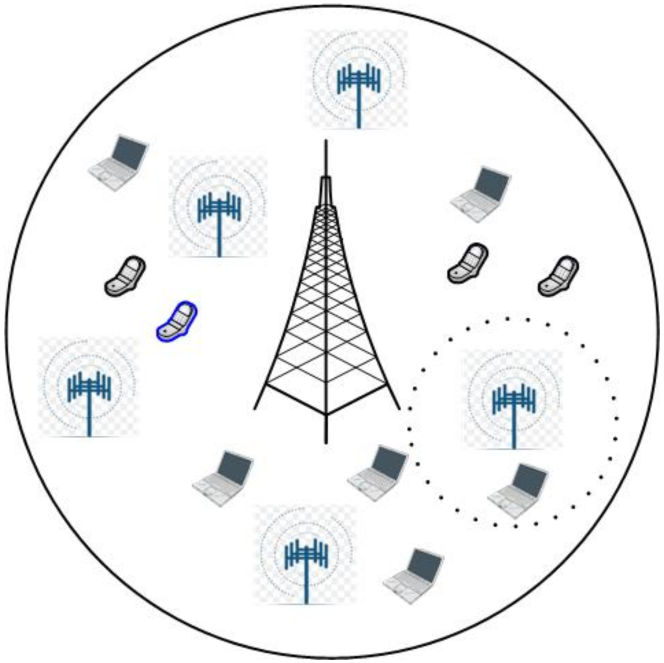
verizon at&t



How does policy influence the strategic behavior of the service providers?

- Licensed vs. unlicensed
- Regulatory constraints (sharing rules)

Spectrum Sharing

- 100 MHz
- Shared with naval radar
- Three-tier sharing rules
  - Incumbents
  - Priority Access Licenses
  - General Access
- Low power
  → small cells

Spectrum Sharing

- 100 MHz
- Shared with naval radar
- Three-tier sharing rules
- Low power
  ➔ small cells

How will the low power / small-cell requirement affect prices, bandwidth allocation, and social welfare?

Assumptions

- SPs manage two networks:
  - Macro-cell / Small-cell
- Two types of users: mobile / fixed
  - Mobile users must connect to macro-cell network
  - Fixed users can connect to macro- or small-cell network
- Utility is a function of the rate received
  - Shared spectrum
    ➔ bandwidth (rate) is split evenly among users

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- SPs manage two networks:
  - Macro-cell / Small-cell
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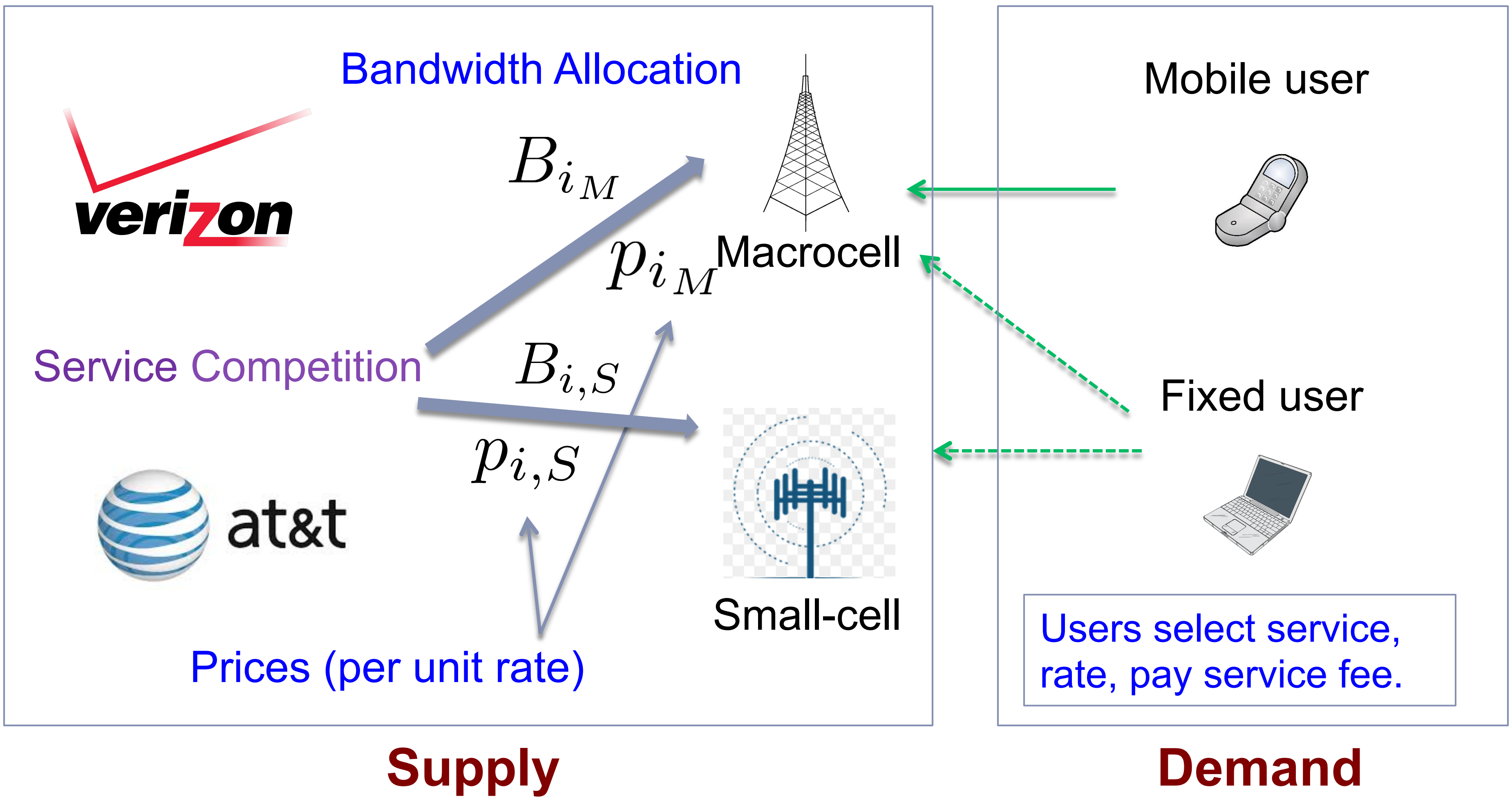
  - Mobile users must connect to macro-cell network
  - Fixed users can connect to macro- or small-cell network
- Utility is a function of the rate received
- Each SP must provide a minimum amount of bandwidth for small cells.

Related Work

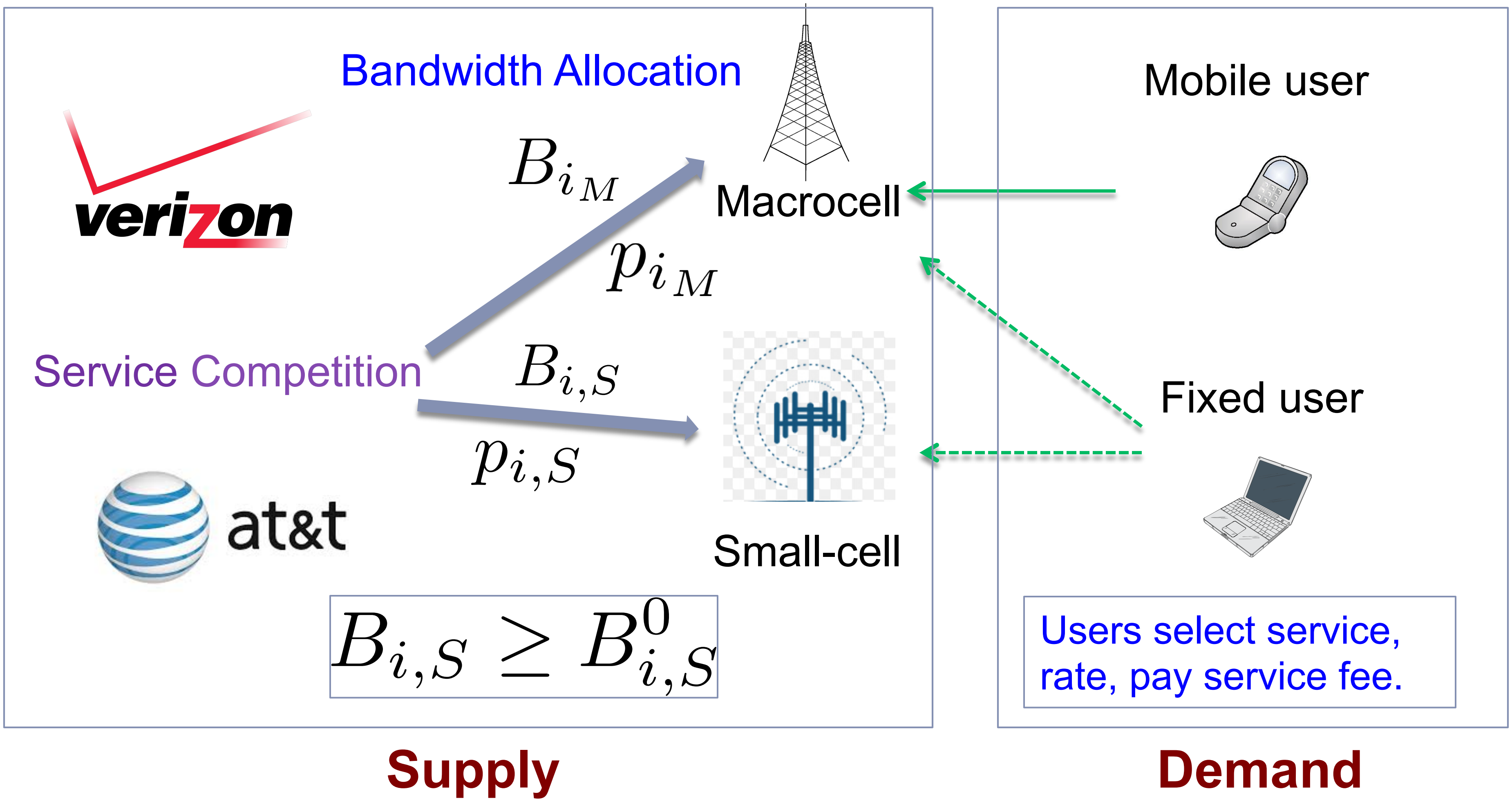
- Chen et al:
  - *Workshop on Smart Data Pricing*, 2015
    Model for competing service providers
  - *Infocom*, 2016
    Licensed and unlicensed spectrum
- Differences from other related work:
  - Two classes of users (mobile/fixed)
  - Providers set prices and optimize bandwidth
  - Constraint on minimum small-cell bandwidth

Model



Bandwidth Allocation
B_{i_M}
p_{i_M}
Macrocell
Service Competition
$B_{i,S}$
$p_{i,S}$
Small-cell
Prices (per unit rate)
Mobile user
Fixed user
Users select service, rate, pay service fee.
Supply
Demand

Model


Bandwidth Allocation
verizon
B_{i_M}
p_{i_M}
Macrocell
Service Competition
$B_{i,S}$
$p_{i,S}$
at&t
Small-cell
$B_{i,S} \geq B^0_{i,S}$
Mobile user
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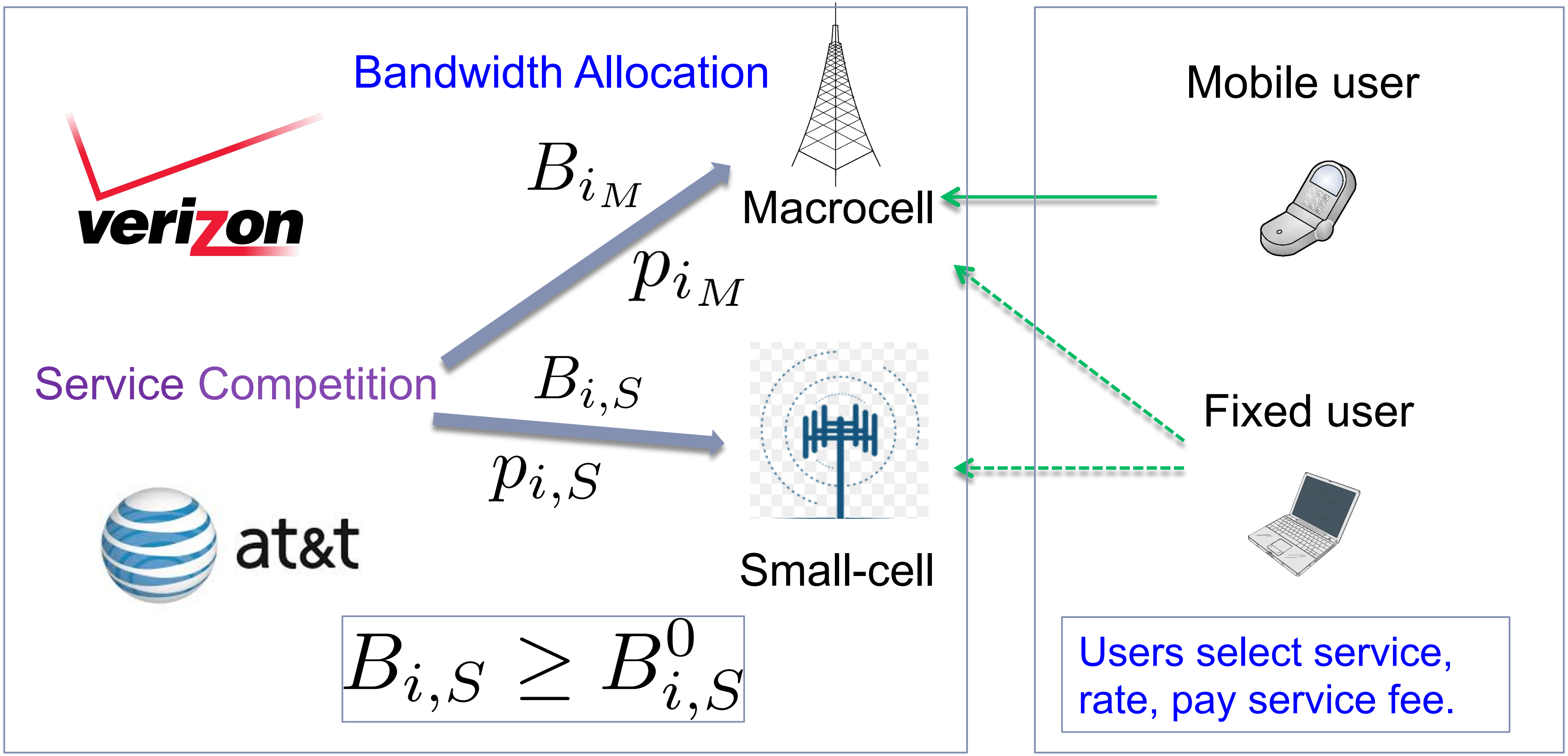
Model

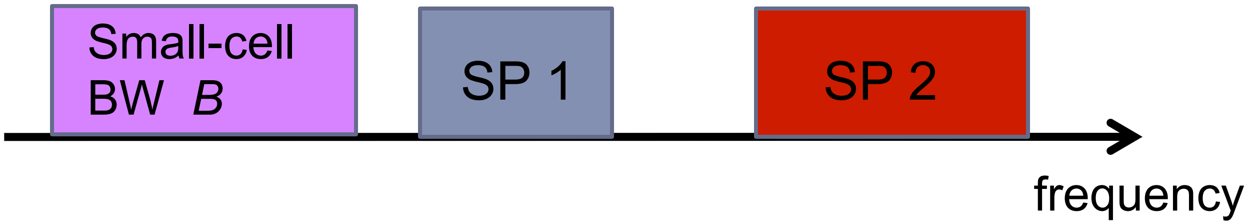


How do the small cell constraints affect bandwidth and prices?

Main Results (1)

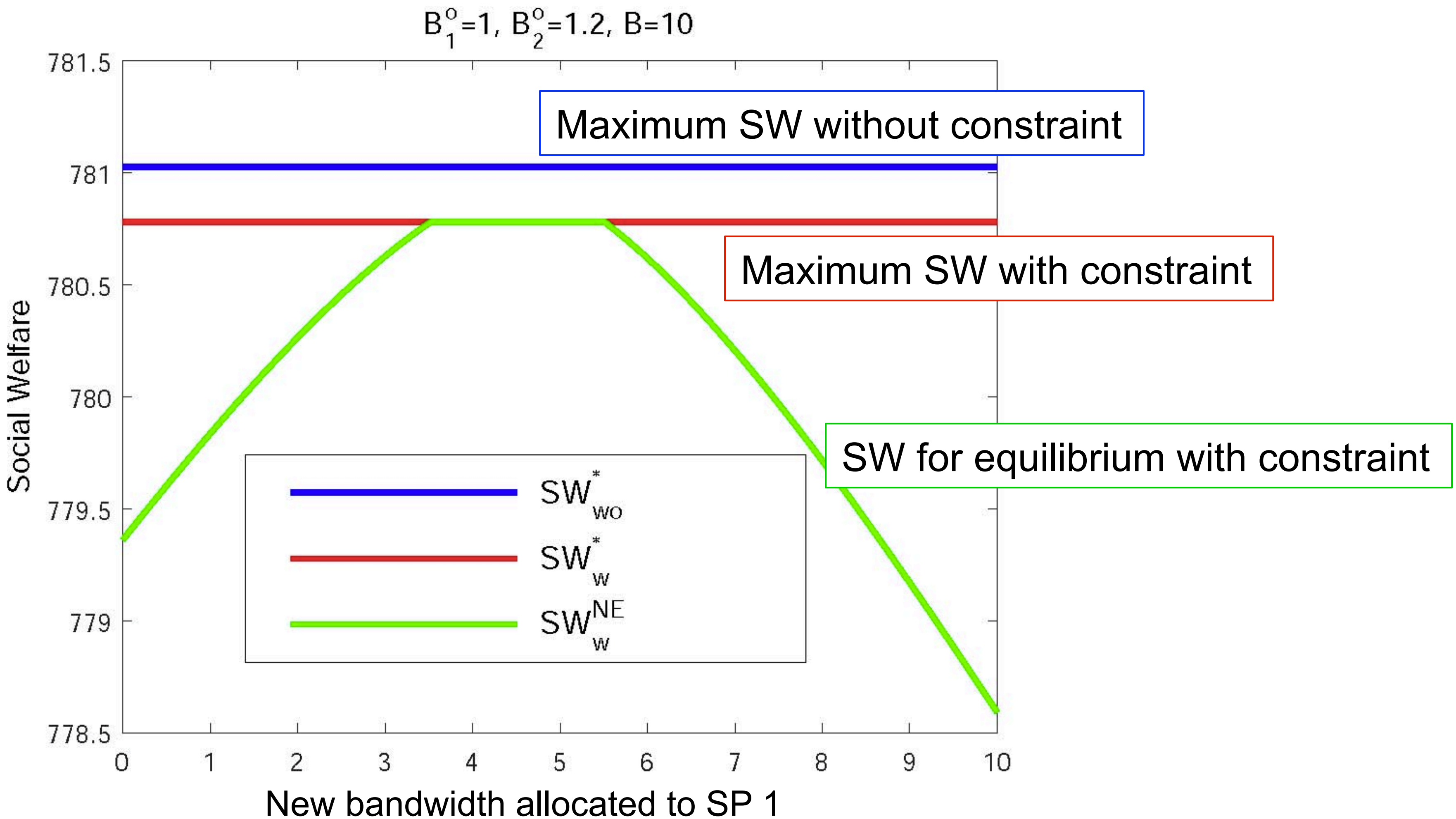
- An equilibrium always exists and is unique.
- Adding the constraints can only decrease social welfare (α-fair utilities).

Adding Small-Cell Bandwidth

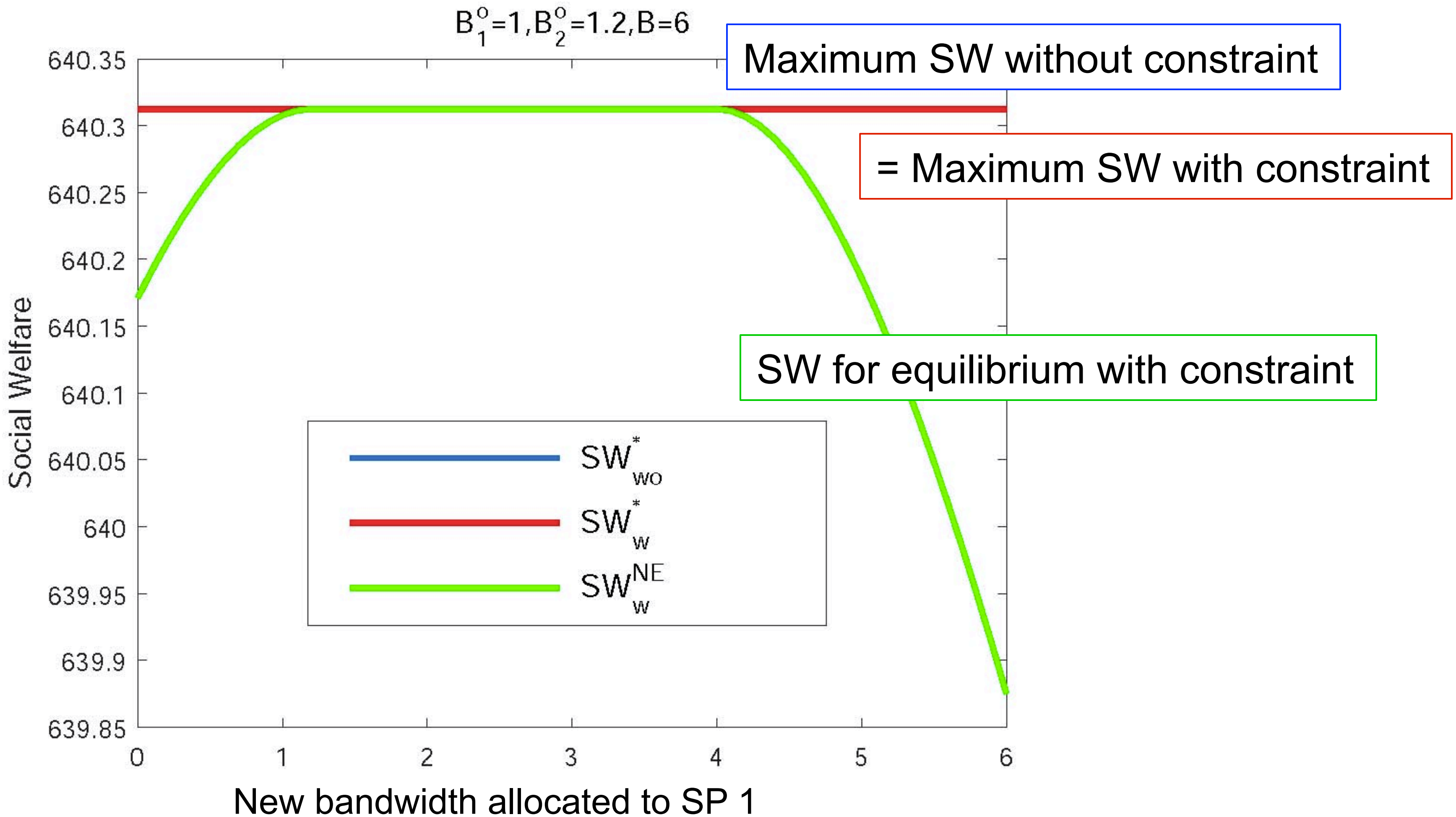


- SPs have exclusive-use bands B_1 and B_2, which can be split between macro and small cells.
- Add bandwidth B designated for small cells.

Social Welfare: Large *B*

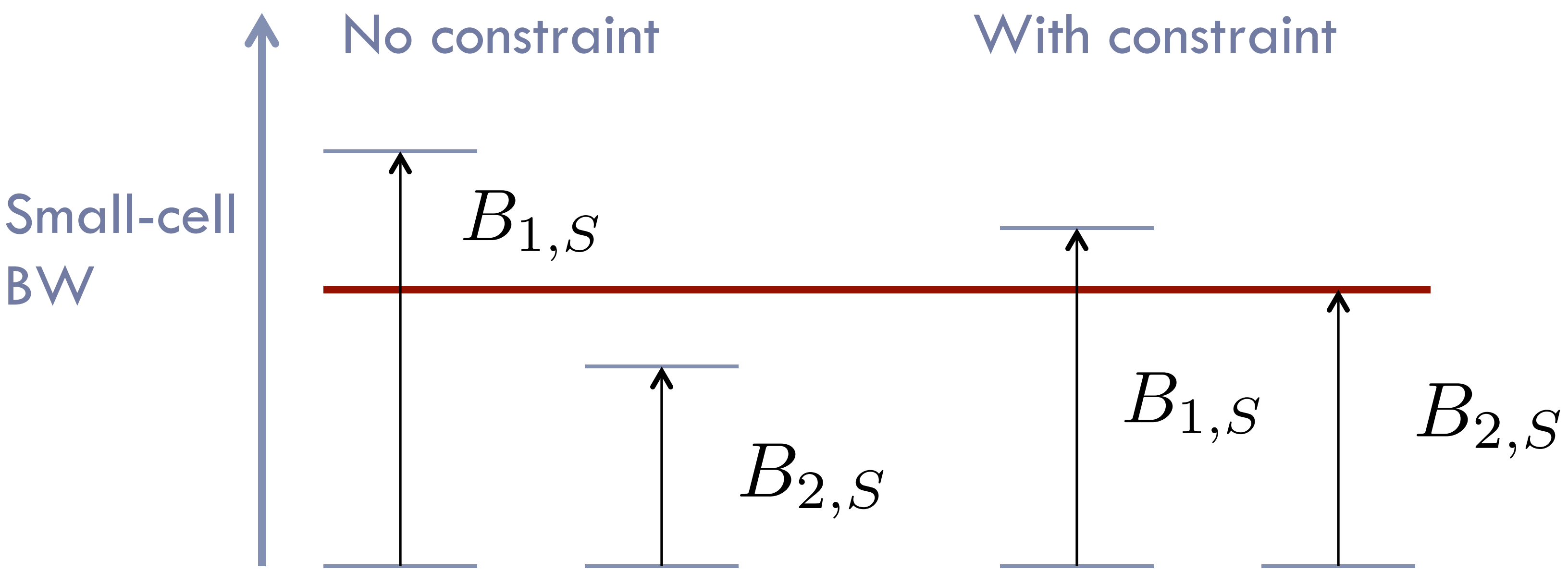


Social Welfare: Smaller *B*



Main Results (2)

- An equilibrium always exists and is unique.
- Possible effect of adding constraint on equilibrium:



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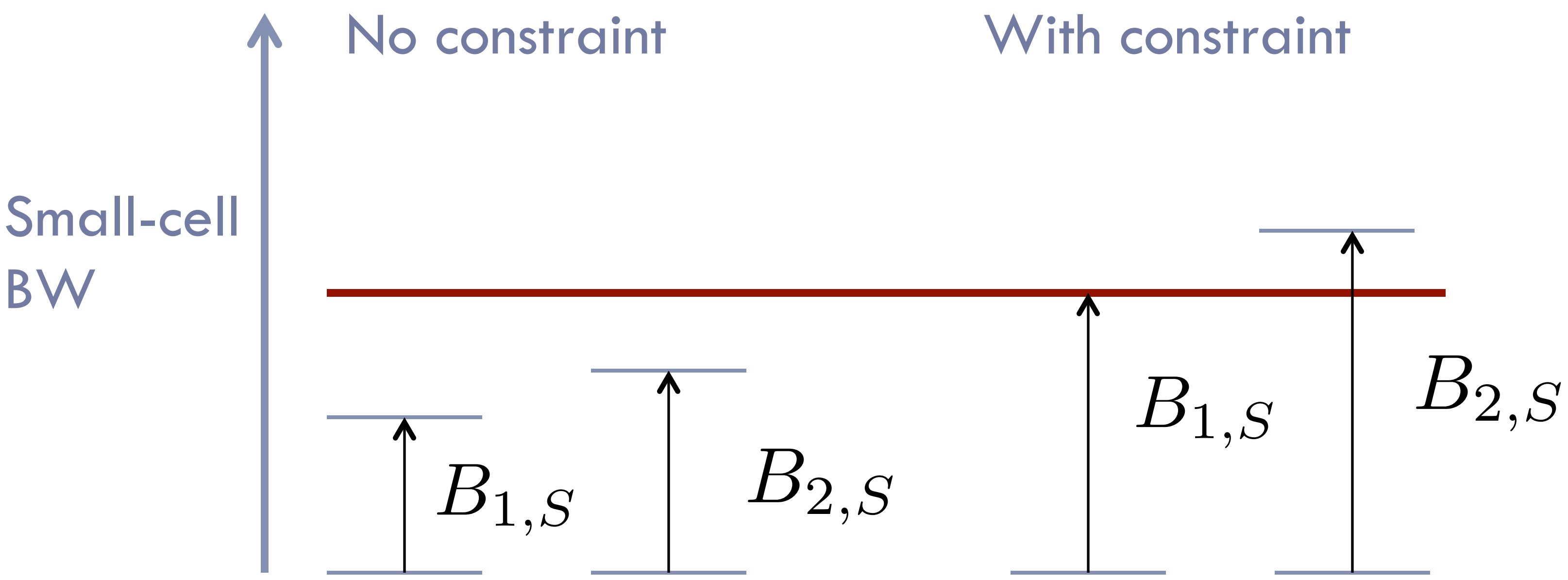
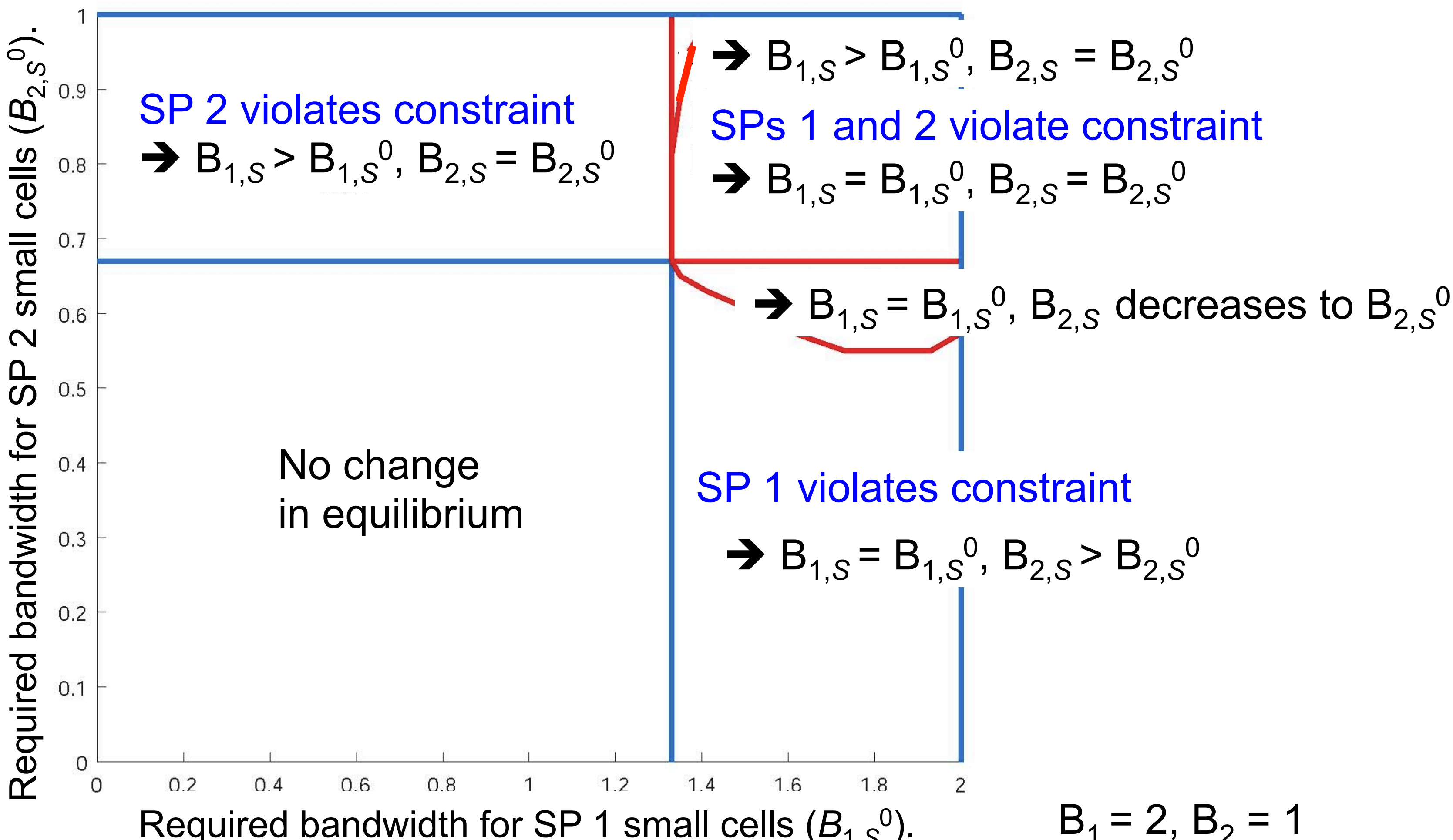


Effect of Constraint on Equilibrium



$B_1 = 2$, $B_2 = 1$

Utility

- Utility for each user is a function of the rate *r*.
- Total rate (capacity) depends on spectral efficiency R_0
  - Macro-cell capacity for SP *i*: $C_{i,M} = B_{i,M}R_0$
  - Small-cell capacity for SP *i*: $C_{i,S} = \lambda_S B_{i,S} R_0$

λ_S >1 accounts for higher density and/or spectral efficiency of small-cell network

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- Will assume the class of α-fair utility functions:

$$u(r) = \frac{r^{1-\alpha}}{1-\alpha}$$

α → 0, *u*(*r*) becomes linear
α → 1, *u*(*r*) becomes logarithmic

Sequential (Two-Stage) Game

1. SPs set bandwidths $B_{i,M}$ $B_{i,S}$
2. SPs set prices $p_{i,M}$ $p_{i,S}$

Fixed users choose network to maximize surplus (utility minus cost): $S(r) = u(r) - p\,r$
rate $r^* = \arg\max S(r) = D(p)$ (demand function)

We will characterize sub-game perfect Nash equilibria:

1. Price equilibrium / user association given bandwidth allocation.
2. Bandwidth allocation given that prices are set according to 1.

Revenue Maximization

$$\max S_i = K_{i,M} p_{i,M} D(p_{i,M}) + K_{i,S} p_{i,S} D(p_{i,S})$$

$$subject\ to\ \ K_{i,M} D(p_{i,M}) \le C_{i,M}$$

$$K_{i,S} D(p_{i,S}) \le C_{i,S}$$

$$B_{i,M} + B_{i,S} \le B_i$$

$$0 \le p_{i,M}, p_{i,S} < \infty$$

$$B_{i,M} \ge 0, \quad B_{i,S} \ge B_{i,S}^0$$

fraction of users
in macro-/small-cell
networks

Social Welfare (Utility) Objective

$$SW = \sum_{i=1}^{N} K_{i,M} u(r_{i,M}) + K_{i,S} u(r_{i,S})$$

With α -fair utility functions the equilibrium maximizes SW without small-cell bandwidth constraints.

Social Welfare Loss

- SW loss occurs when

$$\frac{N_f \lambda_S^{1/\alpha-1}}{N_f \lambda_S^{1/\alpha-1} + N_m} \sum_{i \in \mathcal{N}} B_i < \sum_{i \in \mathcal{N}} B_{i,S}^0$$

- The loss satisfes:

$$\frac{\mathrm{SW}_{\mathrm{w}}^{\mathrm{NE}}}{\mathrm{SW}_{\mathrm{wo}}^{*}} \geq \left(\frac{N_f \lambda_S^{1/\alpha-1}}{N_m + N_f \lambda_S^{1/\alpha-1}} \right)^{\alpha}$$

- Equality holds when $B_{i,S}{}^0 = B_i$ for every SP *i*.

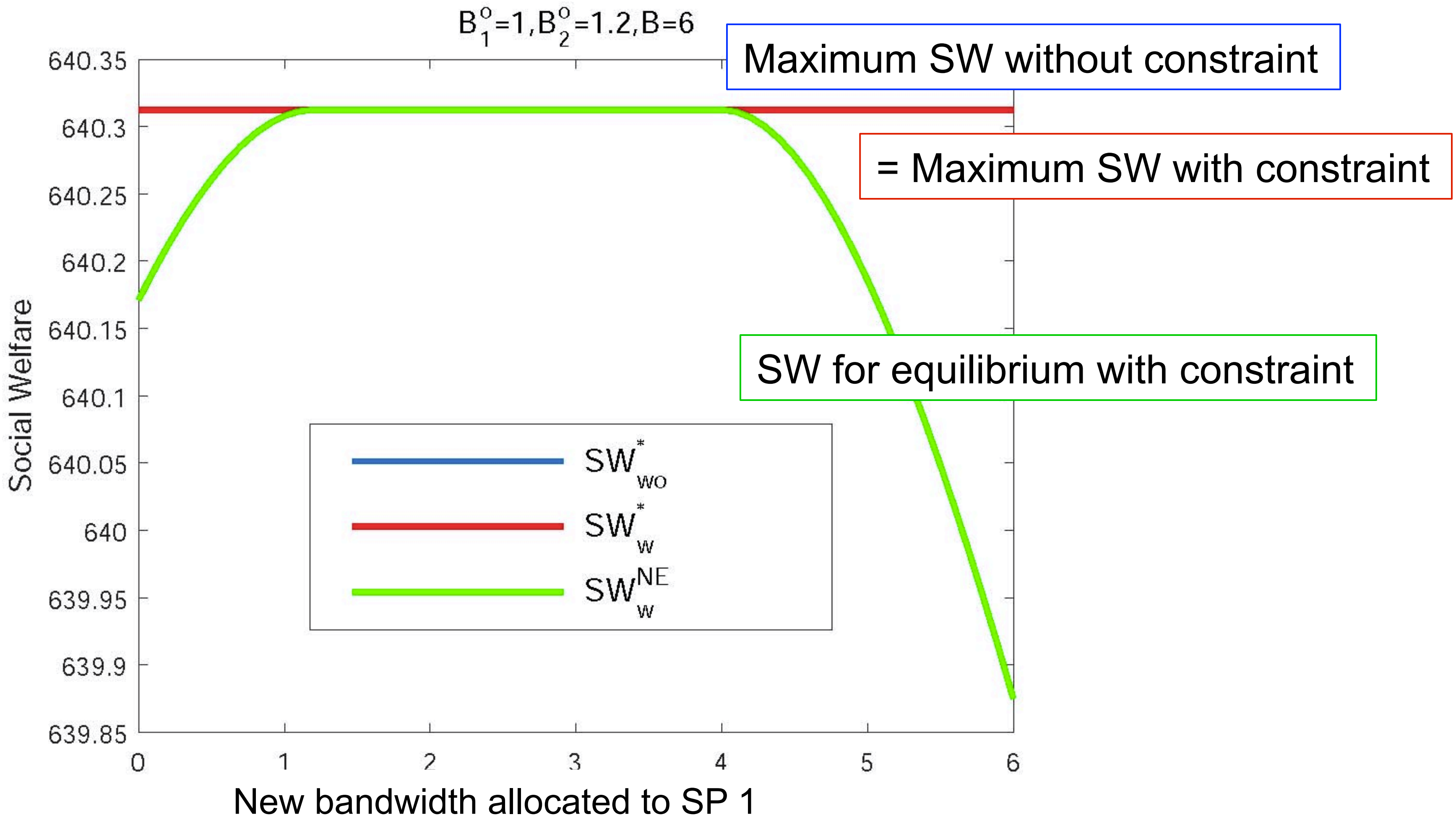
Constraining New Bandwidth

- Given new bandwidth *B*, there a exists a threshold *T* such that if *B* > *T*, constraining *B* for small cells reduces SW.

$$T = \frac{(B_1^o + B_2^o) N_f \lambda_S^{1/\alpha - 1}}{N_m},$$

- If *B* < *T*, *B* can be split between SPs 1 and 2 so that the competitive equilibrium achieves the maximum SW.

Social Welfare: Smaller *B*



Conclusions

- Adding constraints on small-cell bandwidth can change competitive equilibrium and lead to a loss in SW.
- The constraint may cause an SP to reduce its small-cell bandwidth, although the total allocation cannot decrease.
- Constraining new bandwidth B leads to inefficient allocations when B exceeds a threshold.