# Building Robust Cellular Networks

Shivendra Panwar

Based on "The Urge to Merge: When Cellular Providers Pool Capacity," by Sha Hua, Pei Liu and Shivendra S. Panwar, Proceedings of the IEEE ICC, 2012.

## What happens when operators cooperate for business reasons *or after a disaster?*

- Example (US): AT&T merger attempt with T-Mobile *and the recent temporary AT&T T-Mobile "merger" after Sandy*
- Other examples (Europe): Vodafone and O2(Telefonica) in the UK (June 7, 2012), Telenor and Tele2, O2 and Eplus (Germany)
  - Share infrastructure *or share surviving infrastructure*
  - Share spectrum
  - Increase capacity *or maintain capacity*
  - Lower OPEX and CAPEX *or reduce vulnerability*
  - Better service to users *or maintain capacity*
  - Larger revenue and profitability *or improve reliability*

## Traditional Roaming

- Only works when no connection available to the assigned operator (e.g. connect to AT&T when the signal from T-Mobile is weak or non-existent)
- Stringent constraints and high charges

## Extending the roaming concept

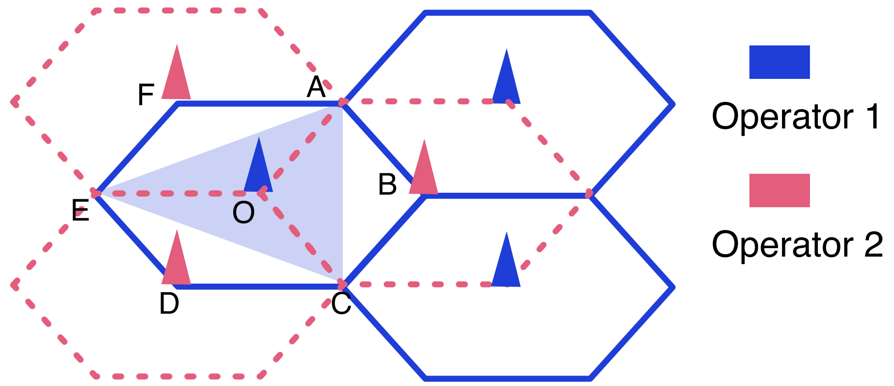
One scenario is that the users can freely access the BSs of either operator by the "strongest signal-first" rule

The principle of increased service through sharing can be extended to a neighborhood femtocell "connectivity island" based on subscribers with backup power supplies and functioning ISP's. This assumes femtocells can at least temporarily be opened to subscribers to competing carriers.

# Hexagonal Layout Example

## Without Cooperation

- Edge users such as those at points B, D and F of Operator 1 will experience poor channel conditions and strong inter-cell interference.




## With Cooperation

- Users at B, D and F will be served by the BSs of Operator 2 and have excellent channels.
- Generally, the users of Operator 1 in the triangles ABC, ECD and EFA will enjoy performance gains. Similar effect happens to users of Operator 2 as well.
- **Capacity is quadrupled, per customer capacity is doubled**

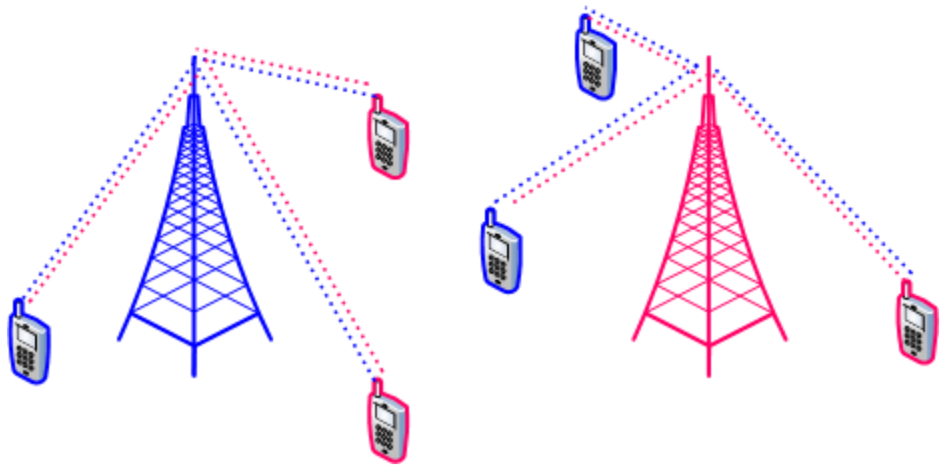
# Two Cooperation Strategies

- **FLEXROAM** (short for "Flexible Roaming")

Cellular operators allow their users to freely connect to any BS of the operator that provides the best signal strength. An update in signaling protocols is required to facilitate this.

- **MERGER**

In addition to FLEXROAM, *operators fully share their spectrum as well*. This could be a business agreement short of a full merger, e.g., MVNO, or temporarily during a man-made or natural disaster



# Average User Rate/Throughput

- **Analytical Modeling**

Based on stochastic geometry, provides tractable and reasonably accurate results.

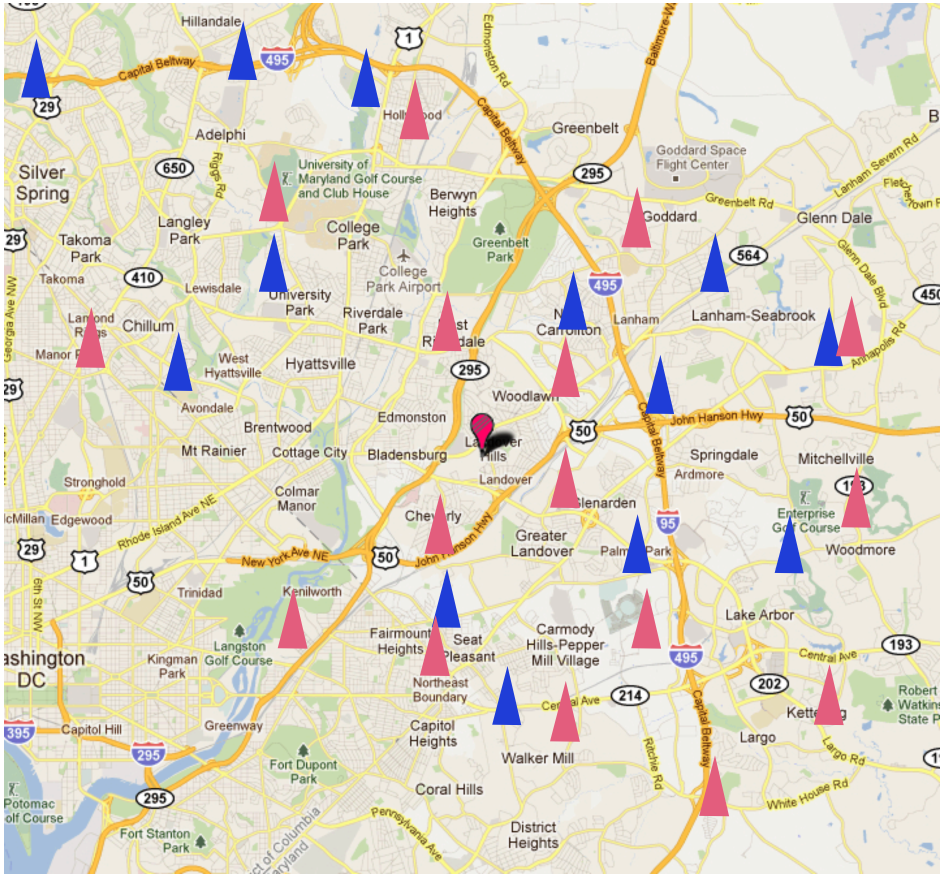
- Assumes Poisson random BS deployment;
- Uses the entire spectrum without sub-channelization;
- Assumes perfect resource allocation following the proportional fairness criterion

- **Simulation**

Monte-Carlo simulations

- Use real BS location data
- OFDMA scheduling algorithm

# Real BS Location Information



Precise coordinates of BSs from two major operators over 20 x 20 km suburban area near Washington D.C.

**MAIN CONCLUSION:**

- Simple cooperation policy with modest changes to existing networks achieve large capacity gain. (FLEXROAM: 45%, MERGER: 100%)
- Network capacity after MERGER of two identical carriers ***quadruples*** the capacity as compared to a single operator

**FUTURE WORK:**

- **More cooperation strategies**. e.g., leveraging relay stations/ mobile devices to forward the traffic, multi-cell cooperation, etc.
- **Load balancing** and **energy efficiency**.
- **Pricing**: Using Game Theory to analyze how to achieve a fair solution and how to share the profits or costs.

Thanks

Q & A

## Analytical Modeling

- Notation

| | |
|---|---|
| $\lambda_i$ | Density of the BSs of operator i |
| $W_i$ | Channel bandwidths used by the BSs of operator i |
| $\eta_i$ | Subscriber density of operator i |
| $P_t$ | Transmission power of the BS |
| $\alpha$ | Path Loss Exponent |

- Main Ref: Poisson Point Processes (PPP) model (Jeff Andrews et al.)

Instead of placing the BSs on a grid, this model assumes that the BSs are distributed according to a PPP. It provides tractable ways to evaluate multi-cell performance.

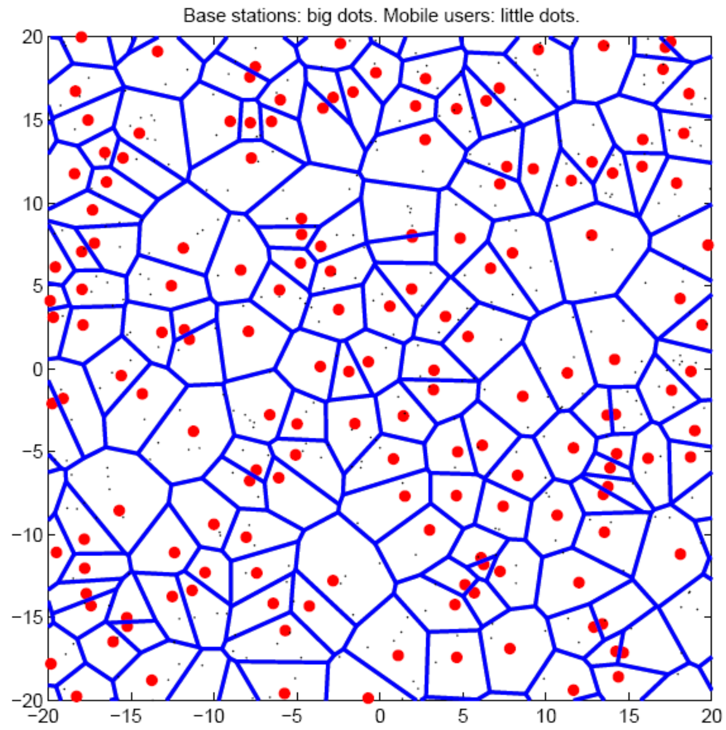
# Jeff Andrews at al. result

- **No Cooperation (NOCOOP)**

**Average User Data Rate:**

$$R_i\left(W_i,\vec{\lambda}\right)=W_i\int_{r>0}e^{-\pi\lambda_i r^2}\int_{t>0}e^{-\frac{N_0 W_i r^{\alpha}\left(e^t-1\right)}{P_t}}F\left(\lambda_i\right)dt2\pi\lambda_i rdr$$

$$F\left(\lambda_i\right)=\exp\left(-\pi\lambda_i r^2\left(e^t-1\right)^{2/\alpha}\int_{\left(e^t-1\right)^{-2/\alpha}}^{\infty}\frac{1}{1+x^{\alpha/2}}dx\right)$$



# Our Analytical Results

- **FLEXROAM:**

**Average User Data Rate:**

$$R_{FLEXROAM}\left(\vec{W},\vec{\lambda}\right)=\frac{\lambda_1}{\lambda_1+\lambda_2}R_1\left(W_1,\vec{\lambda}\right)+\frac{\lambda_2}{\lambda_1+\lambda_2}R_2\left(W_2,\vec{\lambda}\right)$$

where

$$R_i\left(W_i,\vec{\lambda}\right)=W_i\int_{r>0}e^{-\pi\left(\lambda_1+\lambda_2\right)r^2}\int_{t>0}e^{-\frac{N_0W_ir^{\alpha}\left(e^t-1\right)}{P_t}}F\left(\lambda_i\right)dt\,2\pi\left(\lambda_1+\lambda_2\right)rdr$$

$$F\left(\lambda_i\right)=\exp\left(-\pi\lambda_ir^2\left(e^t-1\right)^{2/\alpha}\int_{\left(e^t-1\right)^{-2/\alpha}}^{\infty}\frac{1}{1+x^{\alpha/2}}dx\right)$$

# Our Analytical Results

**FLEXROAM: Average User Throughput** (assuming proportional fair scheduling

$$Th_{FLEXROAM}\left(\vec{W},\vec{\lambda},\vec{\eta}\right)=R_{FLEXROAM}\left(\vec{W},\vec{\lambda}\right)\frac{\lambda_1+\lambda_2}{\eta_1+\eta_2}$$

**MERGER:** average user data rate and average user throughput are analyzed similarly.

$$R_{MERGER}\left(\vec{W},\vec{\lambda}\right)=R_{NOCOOP}\left(W_1+W_2,\lambda_1+\lambda_2\right)$$

$$Th_{MERGER}\left(\vec{W},\vec{\lambda},\vec{\eta}\right)=R_{MERGER}\left(\vec{W},\vec{\lambda}\right)\frac{\lambda_1+\lambda_2}{\eta_1+\eta_2}$$

# Special Case: Cooperation among same size operators

We make following assumptions to simplify our results:

- $W_1 = W_2 = W, \lambda_1 = \lambda_2 = \lambda, \eta_1 = \eta_2 = \eta$
- No noise, as cellular networks are typically interference limited.

## Main Results

$$Th_{FLEXROAM}\left(\vec{W},\vec{\lambda},\vec{\eta}\right) = \frac{\lambda W}{\eta}\int_{t>0}\frac{2}{2+G(t)}dt \qquad G(t) = \left(e^t - 1\right)^{2/\alpha}\int_{\left(e^t-1\right)^{-2/\alpha}}^{\infty}\frac{1}{1+x^{\alpha/2}}dx$$

$$Th_{MERGER}\left(\vec{W},\vec{\lambda},\vec{\eta}\right) = \frac{\lambda W}{\eta}\int_{t>0}\frac{2}{1+G(t)}dt$$

$$Th_{NOCOOP}\left(\vec{W},\vec{\lambda},\vec{\eta}\right) = \frac{\lambda W}{\eta}\int_{t>0}\frac{1}{1+G(t)}dt$$

| | $\alpha = 3.5$ | $\alpha = 4$ |
|---|---|---|
| FLEXROAM | 45.9% | 44.6% |
| MERGER | 100% | 100% |

Per user throughput improvement compared to NOCOOP

NYU WIRELESS

NYU-poly POLYTECHNIC INSTITUTE OF NYU

WICAT WIRELESS INTERNET Center for Advanced Technology

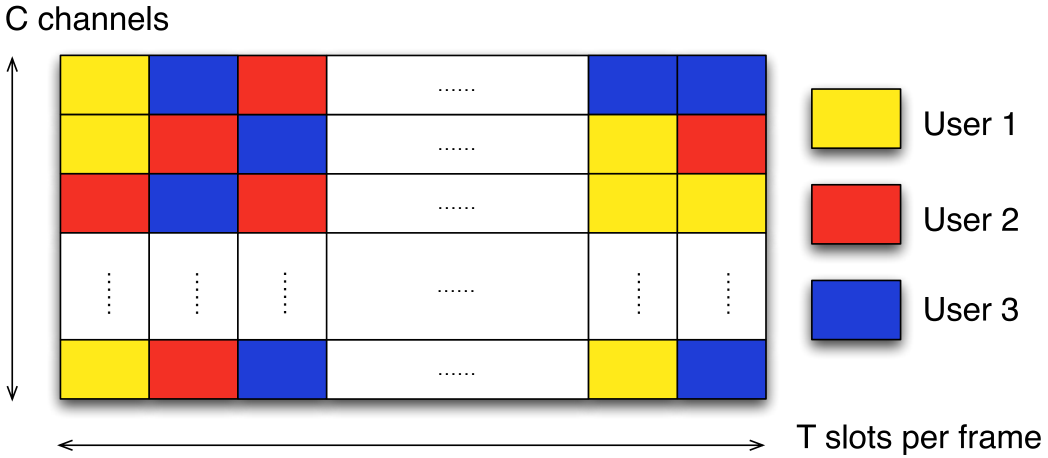
# OFDMA System Simulation

To validate the network performance in a **practical multi-cell system**, we consider:

- Subchannelization.
- Fair subchannel-user resource allocation.
- Real BS locations.

**We present an OFDMA resource allocation algorithm**

- Can be applied to multi-cell environment
- Achieve proportional fairness
- Low computational complexity




OFDMA channel resources

# Numerical Results

- **Simulation Settings**

Fix the parameters for operator 1:

BS density $\lambda_1$ = 16 / 400000000

User density $\eta_1$ = 100

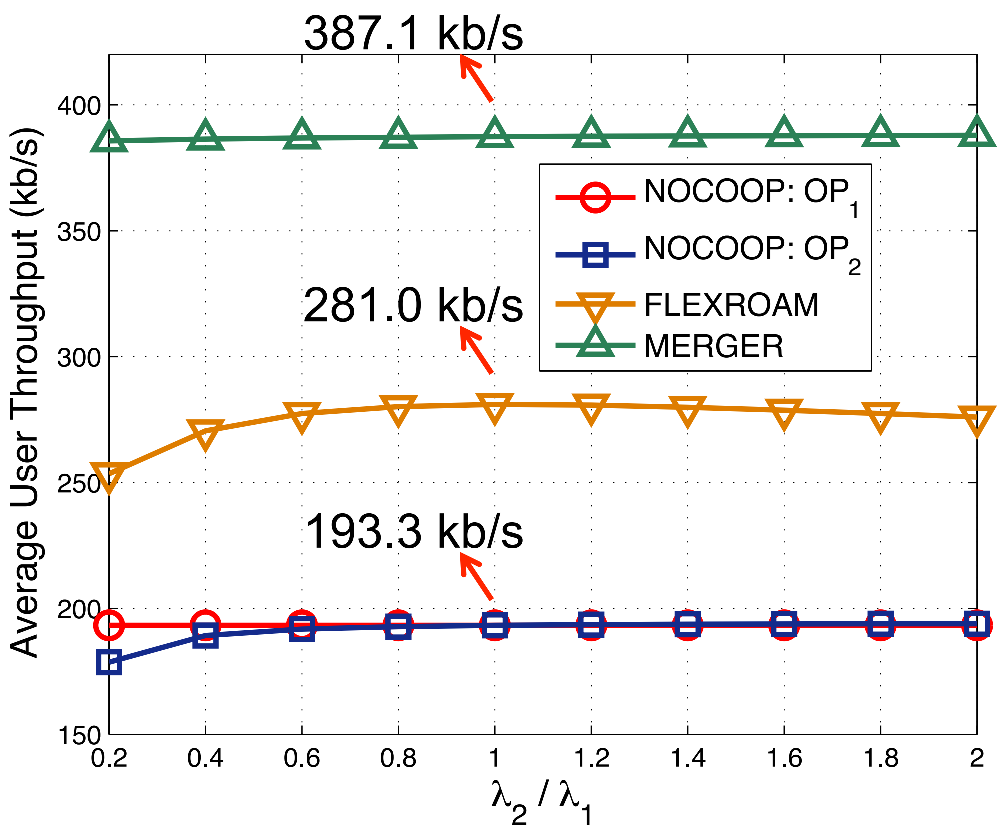
Bandwidth $W_1$ = 10 MHz

$\lambda_1$

Adjust the parameters of operator 2

- **The impact of BS density**
- **The impact of user density**
- **The impact of bandwidth**

# The Impact of BS Density




User density:

$$\eta_2 = \eta_1$$

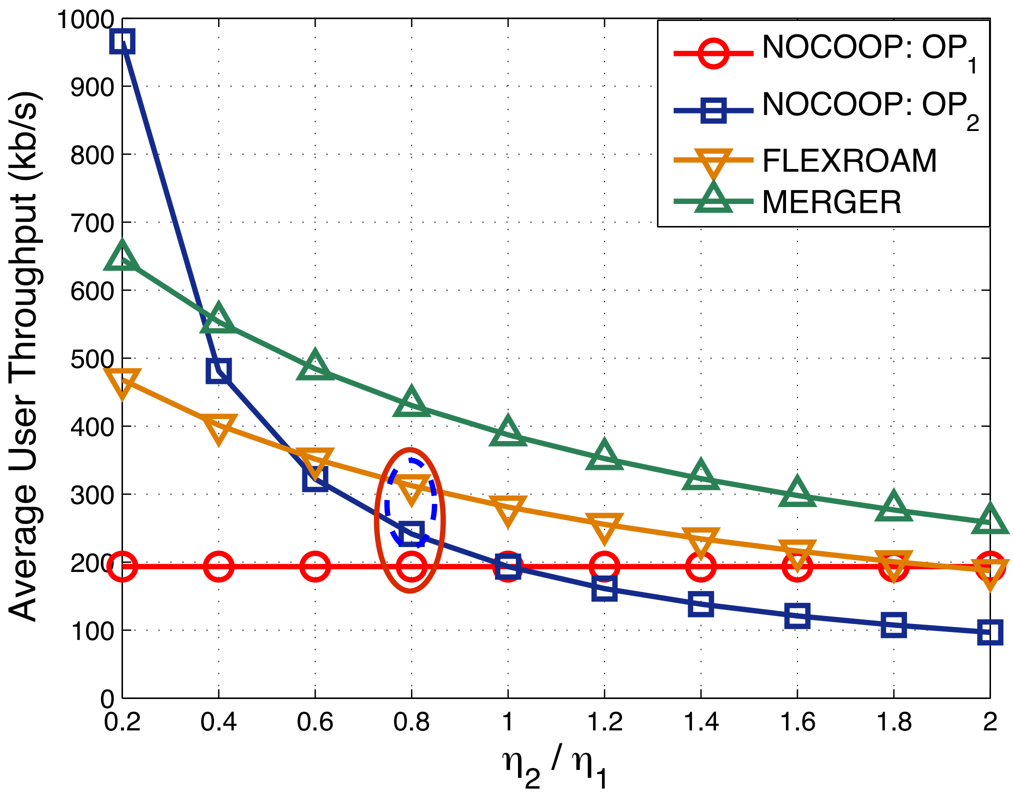
Bandwidth:

$$W_2 = W_1$$

POLYTECHNIC INSTITUTE OF NYU

WIRELESS INTERNET Center for Advanced Technology

# The Impact of User Density



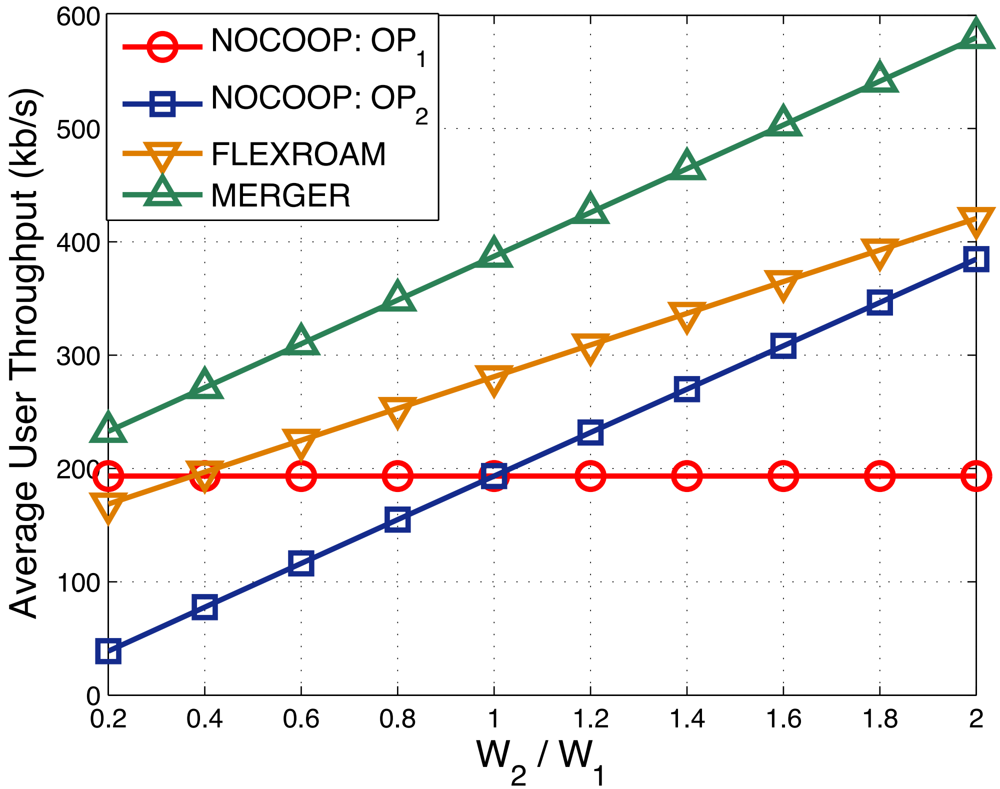

BS density:

$$\lambda_2 = \lambda_1$$

Bandwidth:

$$W_2 = W_1$$

# The Impact of Bandwidth




BS density

$$\lambda_2 = \lambda_1$$

User density:

$$\eta_2 = \eta_1$$

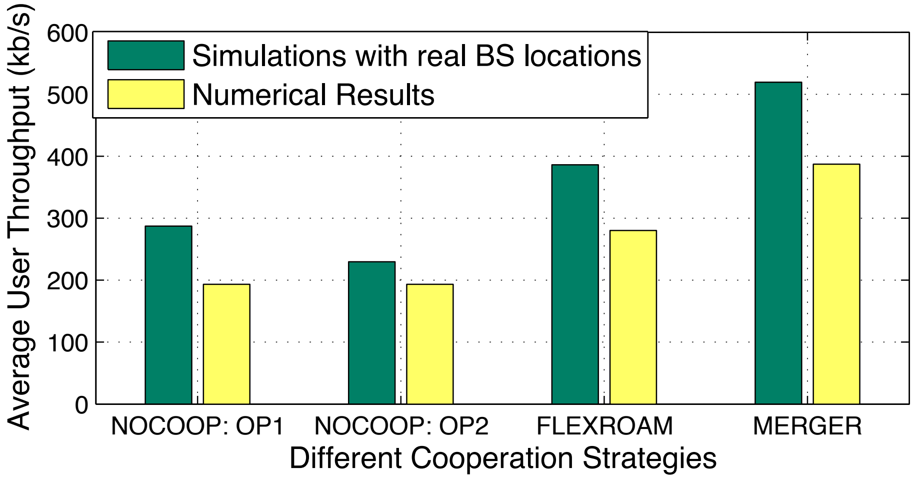
# Performance with Real BS Locations

- **Simulation Settings**
- Consider two operators with real BS location;
- Mobile devices are uniformly deployed in the 20 km x 20 km area;
- IEEE 802.16m evaluation methodology document

TABLE I
OFDMA SYSTEM PARAMETERS

| | |
|---|---|
| Number of subchannels | 32 |
| Number of slots per frame | 60 |
| BS Transmit Power | 46 dBm |
| Noise power spectrum density $N_0$ | -174 dBm |
| Channel bandwidth | 10 MHz |

- **Network performance**




- **The impact of BS density**