

Joint Transmission in Cellular Networks: Scheduling and Stability

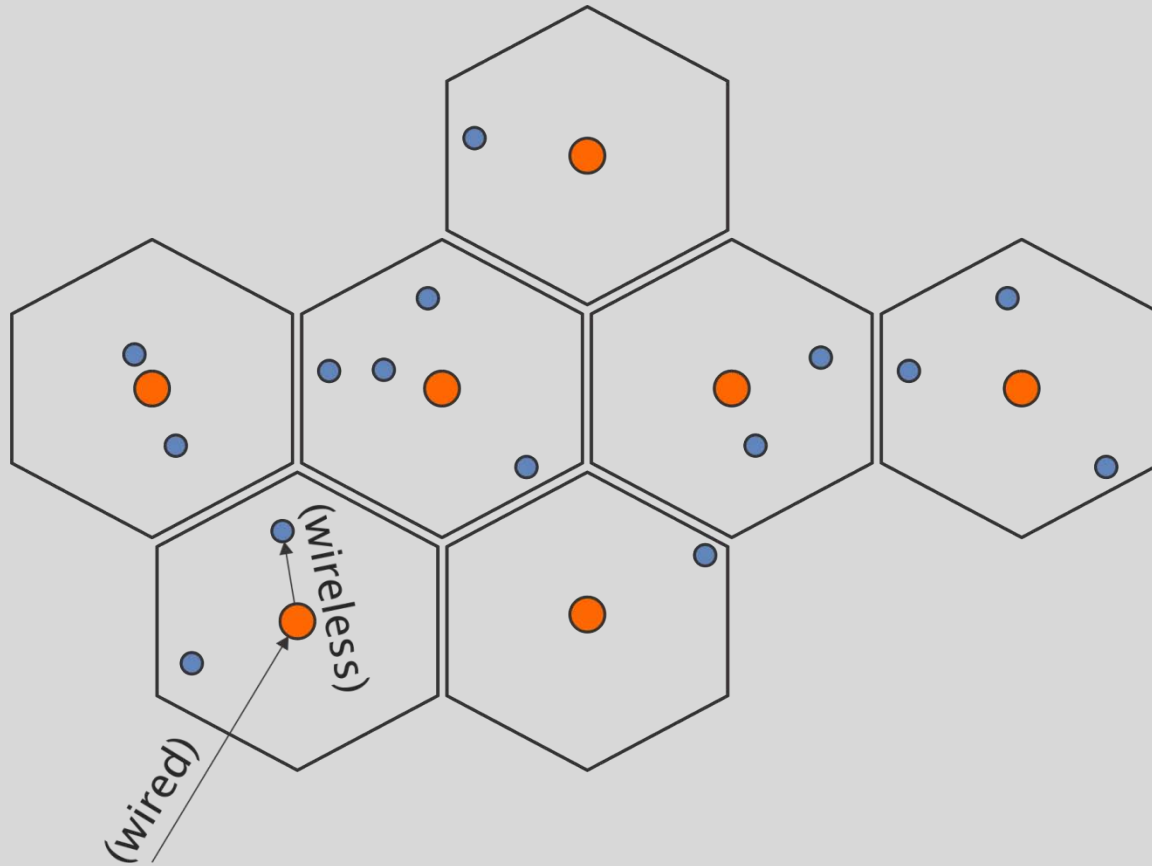
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(Columbia University)

The logo for the Centrum voor Wiskunde en Informatica (CWI) is a red parallelogram with the letters 'CWI' in white, bold, sans-serif font.

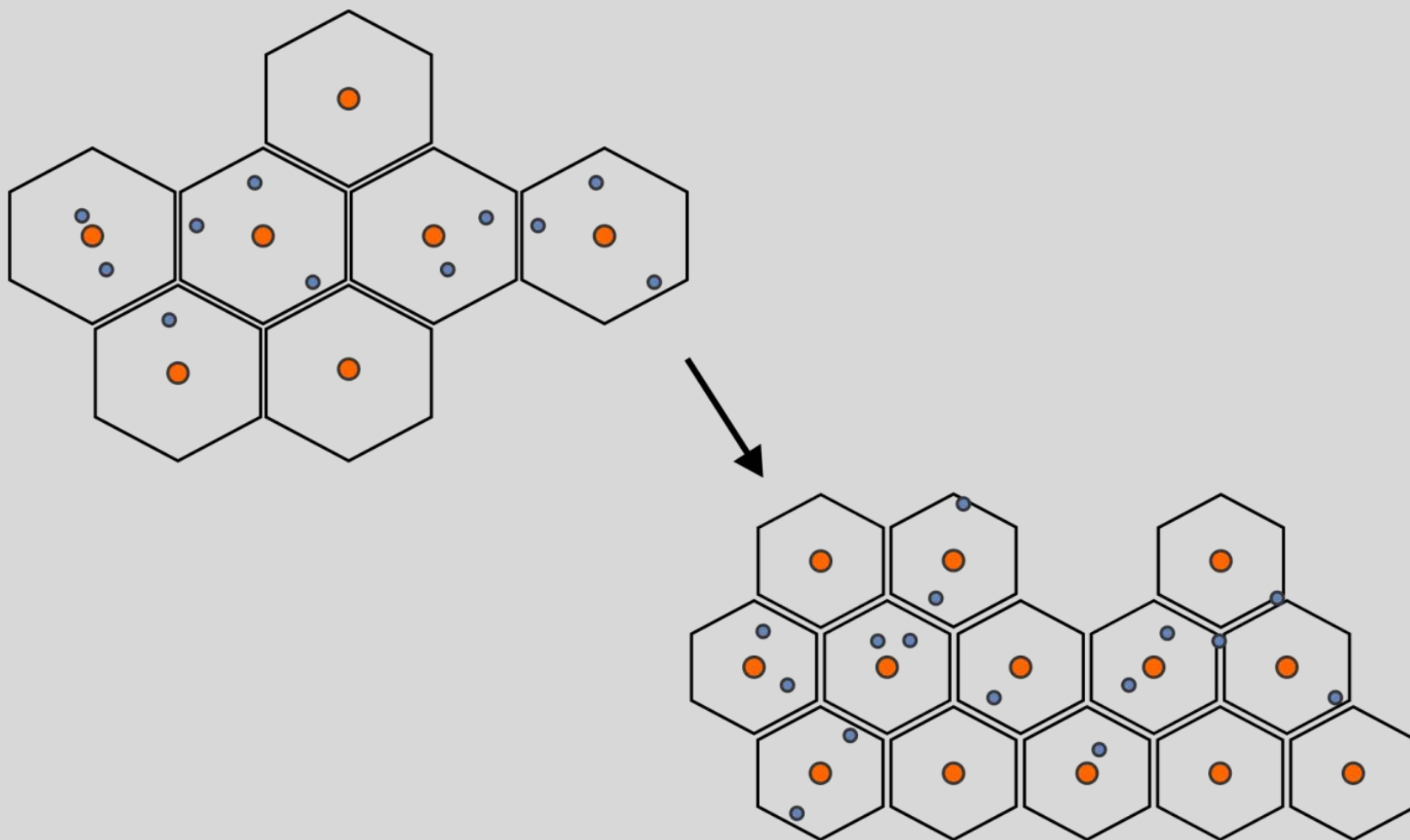
CWI

Cellular networks



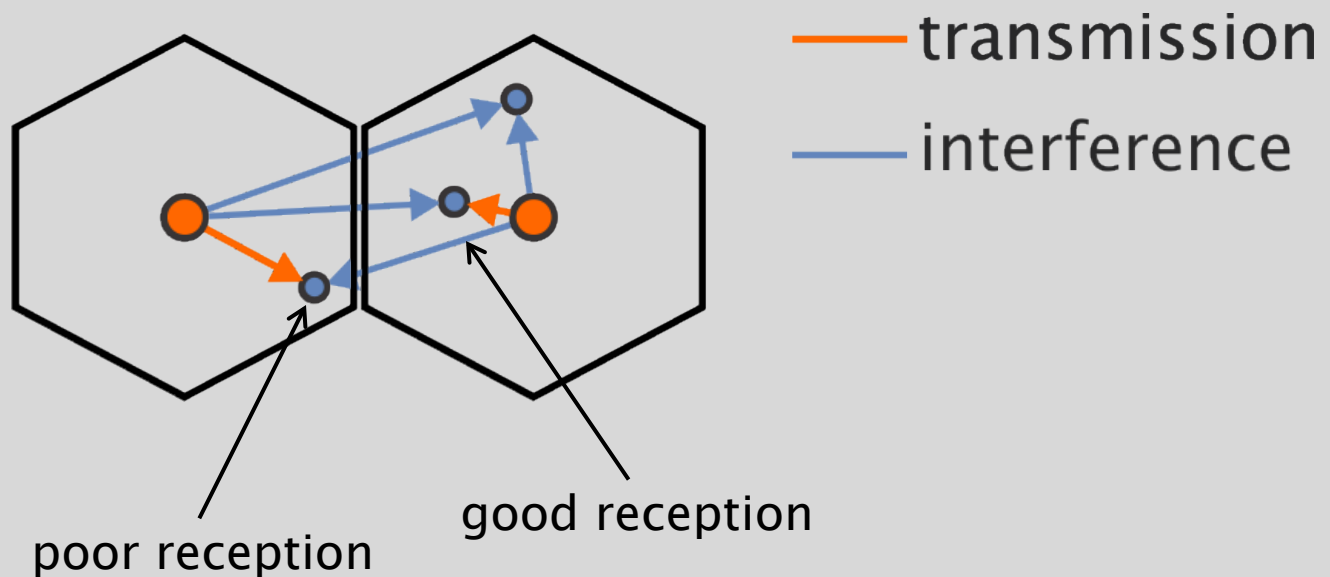
Downlink channel:

- **users** are associated to closest **base station** (BS)
- BSs transmit to users



Reduce **cell size** to satisfy increasing demand for **capacity**

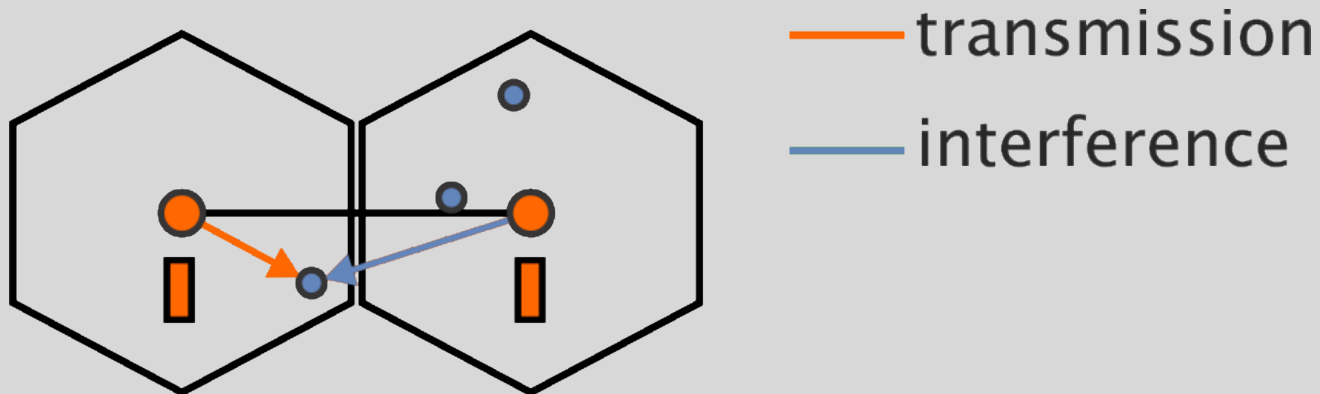
By reducing cell size we increase the number of cell-edge users that have little or no reception



Joint transmission

LTE-Advanced standard introduces **joint-transmission**:

- packet is **forwarded on backhaul** to secondary BS
- serving & secondary BS **transmit** packet **simultaneously**



Joint-transmission **pros** & **cons**:

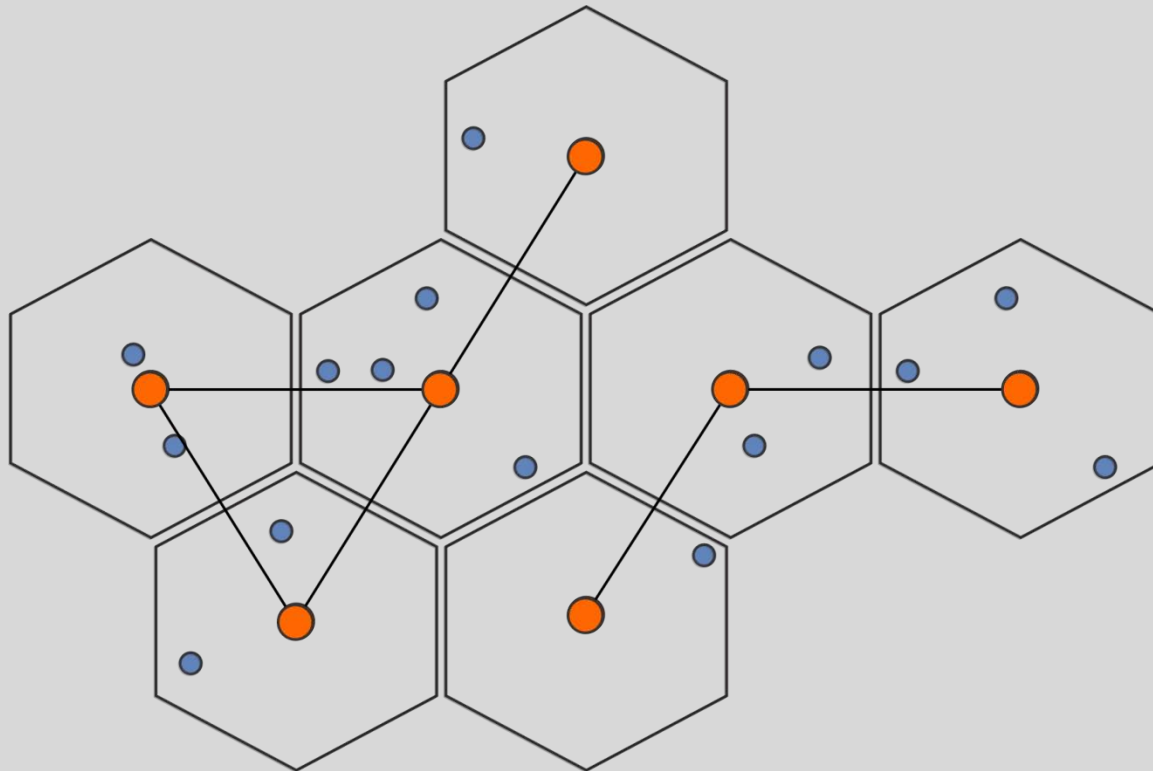
- **pro**: better reception cell-edge users
- **con**: uses two BSs instead of one

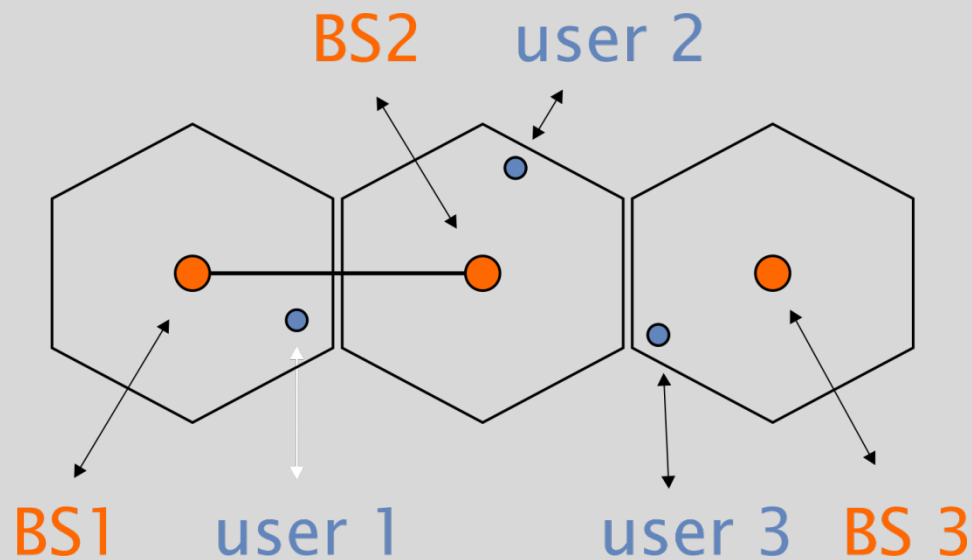
Question: **how** should we use joint-transmission, and **how much** does this benefit users?

model outline

Three components to the model:

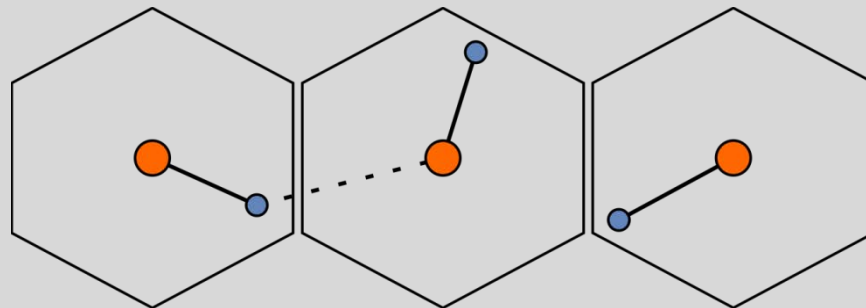
- B base stations
- N users
- graph of backhaul links





Users are assigned a **serving** BS and maybe **secondary** BS

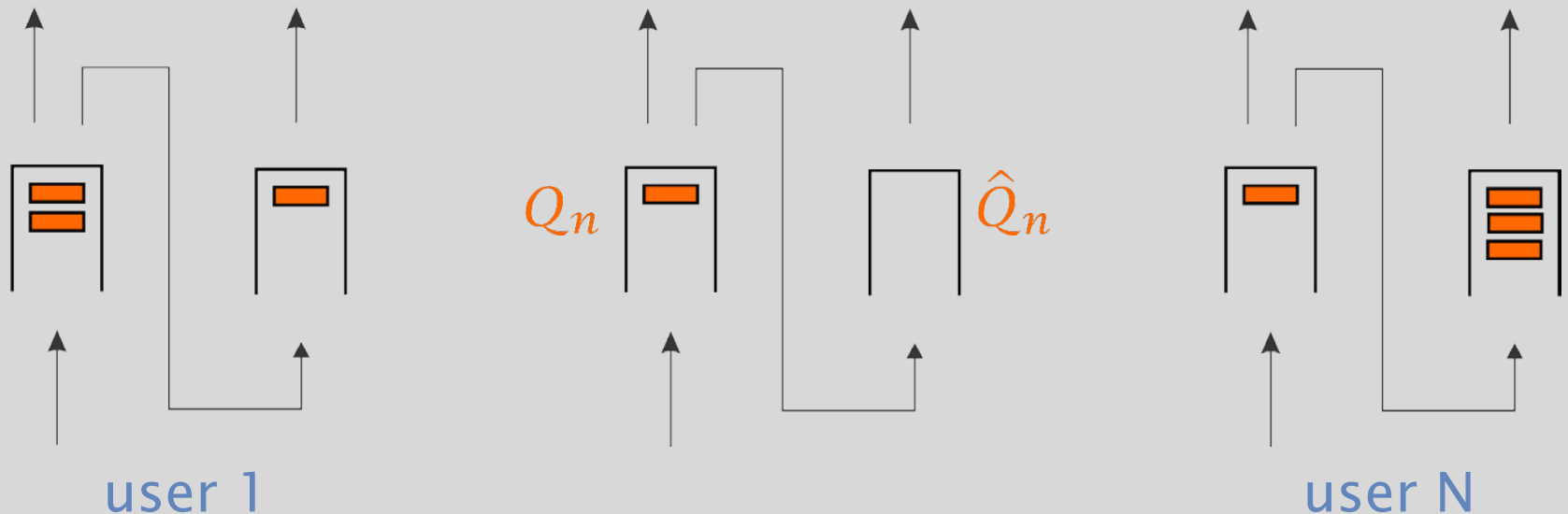
- **serving** for all normal (single) transmissions
- **secondary** helps **serving** BS for all joint transmissions
- only if a **backhaul link** is available



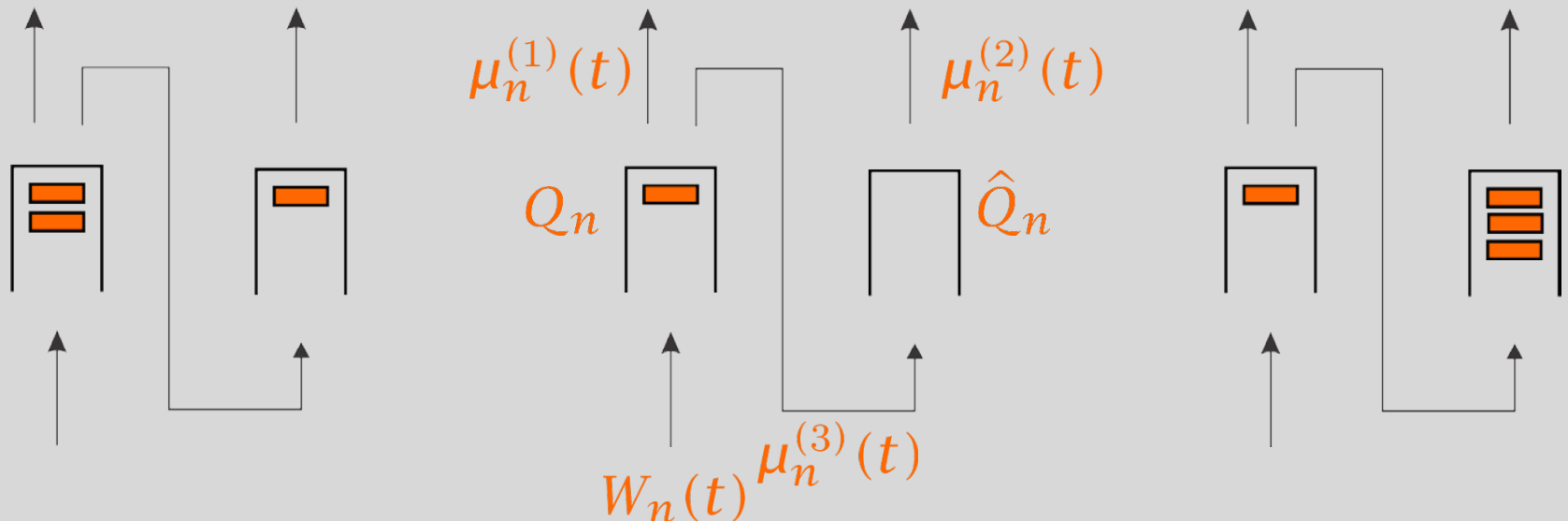
Queueing model

The dynamics:

- time is slotted, $t = 0, 1, \dots$
- each user n is associated with one or two queues:
- queue Q_n of length $L_n(t)$ (single-transmission)
- queue \hat{Q}_n of length $\hat{L}_n(t)$ (joint-transmission)



- in slot t , $W_n(t)$ new packets arrive at Q_n
- from Q_n , packets can be sent to \hat{Q}_n , or **single-transmitted**
- from \hat{Q}_n , packet can be **joint-transmitted**
- successfully transmitted packets (both **single** and **joint**) leave the system
- Denote by $\mu_n^{(i)}(t)$ the number of packets



Solve a scheduling problem to determine $\mu_n^{(i)}(t)$

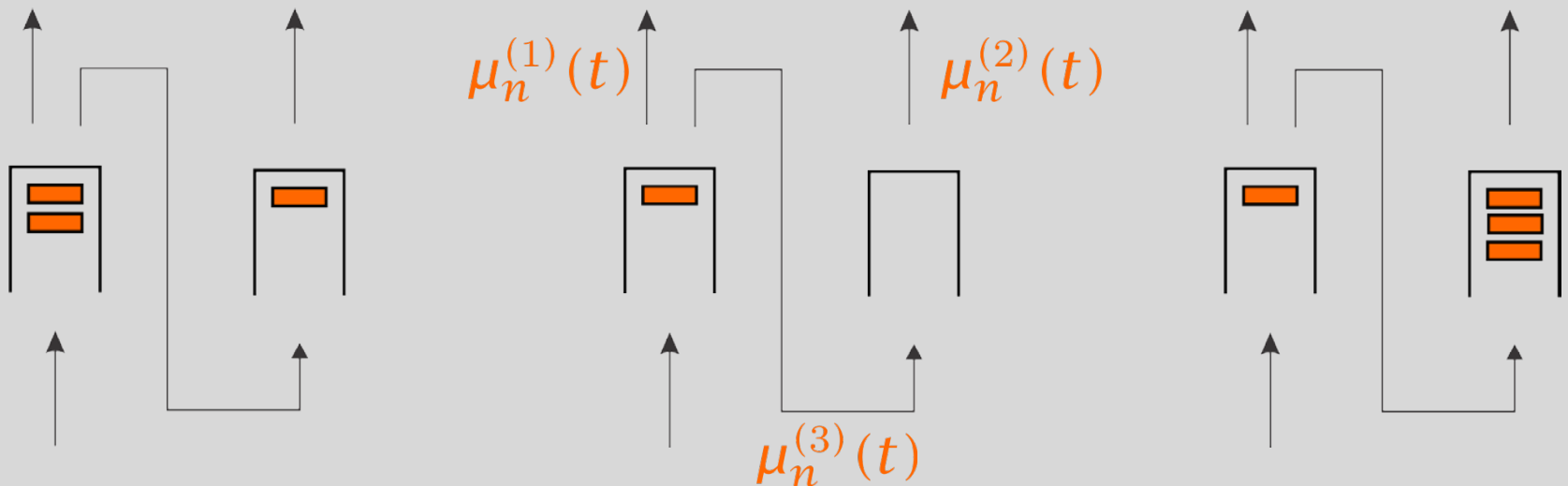
$$\mu_n^{(i)}(t) \sim \text{Bin}(m_n^{(i)}, p_n^{(i)})$$

packets scheduled

success probability

The $m_n^{(i)}$ are subject to scheduling constraints

- the constraints capture **dependence** between users
- JT improves success probability: $p_n^{(1)} < p_n^{(2)}$



arrivals

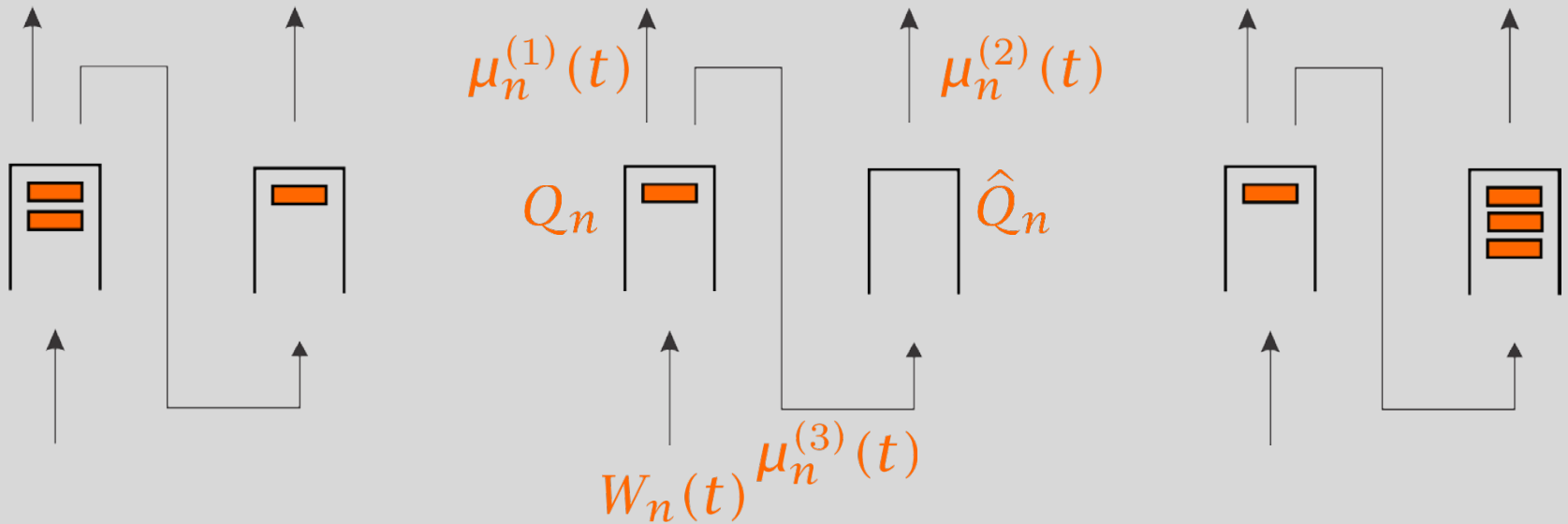
single-transmission

$$L_n(t+1) = L_n(t) + W_n(t) - \mu_n^{(1)}(t) - \mu_n^{(3)}(t)$$

$$\hat{L}_n(t+1) = \hat{L}_n(t) + \mu_n^{(3)}(t) - \mu_n^{(2)}(t)$$

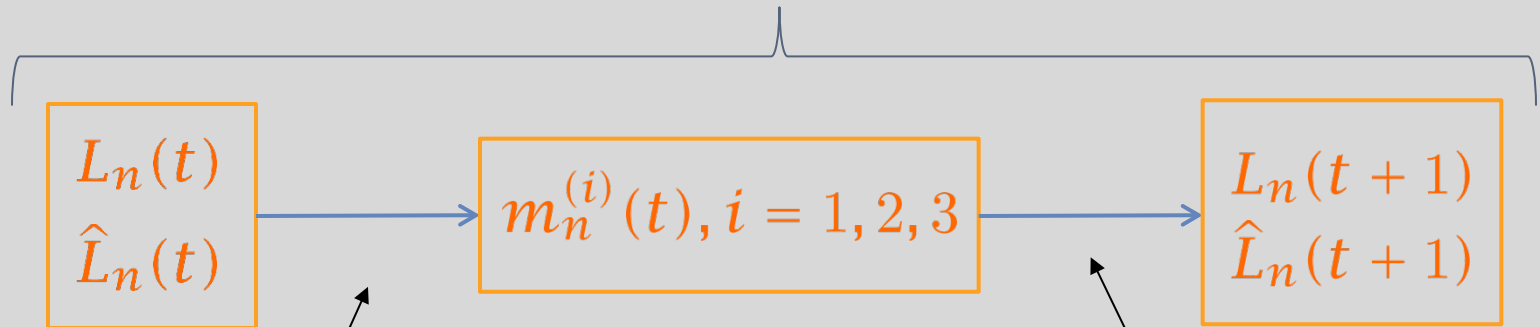
joint-transmission

backhaul



Scheduling & queueing

step II: stochastic queueing model



solve scheduling problem

step I: deterministic scheduling problem

transmit using schedule, random

$\mu_n^{(i)}(t), i = 1, 2, 3$

OFMDA joint scheduling (OJS) problem

The OJS problem can be written as follows:

$$\max_{\mathbf{x}, \mathbf{y}, \mathbf{z}} \sum_{i=1}^I z_i u(i, 1) + y_i u(i, 0) =: U(\mathbf{z}, \mathbf{y})$$

no simultaneous
wireless & backhaul

allocation of scheduled blocks

objective function

$$\text{s.t. } z_i + y_i \leq 1, \quad \forall i \in \mathcal{I},$$

$$\sum_{\{i: a \in h(i)\}} z_i \leq S, \quad \forall a \in \mathcal{B}; \quad \sum_{\{i: h(i)=l\}} y_i \leq K, \quad \forall l \in \mathcal{C},$$

$$\sum_{s=1}^S x_{is} = z_i, \quad \forall i \in \mathcal{I}; \quad y_i = 0, \quad \forall i \text{ s.t. } \beta(i) = 1,$$

$$\sum_{\{i: b \in h(i)\}} x_{is} \leq 1, \quad \forall b \in \mathcal{B} \quad \forall s \in \mathcal{S},$$

capacity constraints

decision variables

$$z_i \in \{0, 1\}, \quad y_i \in \{0, 1\}, \quad \forall i \in \mathcal{I},$$

$$x_{is} \in \{0, 1\}, \quad \forall i \in \mathcal{I} \quad \forall s \in \mathcal{S}.$$

Proposition

OJS is strongly NP-hard

We show this by reduction from minimum edge coloring

Decomposition framework

To devise efficient algorithms for OJS, decompose as follows

$$\begin{array}{ll} \max_{\mathbf{x}, \mathbf{y}, \mathbf{z}} U(\mathbf{z}, \mathbf{y}) \\ \text{s.t. constraints}(\mathbf{x}, \mathbf{y}, \mathbf{z}) \text{ hold} \end{array}$$

OJS

$$\begin{array}{ll} \max_{\mathbf{y}, \mathbf{z}} U(\mathbf{z}, \mathbf{y}) \\ \exists \mathbf{x} \text{ s.t. constraints}(\mathbf{x}, \mathbf{y}, \mathbf{z}) \text{ hold} \end{array}$$

JTK

$$\begin{array}{ll} \text{find}_{\mathbf{x}} \\ \text{s.t. constraints}(\mathbf{x}, \mathbf{y}^*, \mathbf{z}^*) \text{ hold} \end{array}$$

JTC



Decomposition framework

We use decomposition for **approximation algorithms** and efficient algorithms for bipartite graphs

$\max_{\mathbf{y}, \mathbf{z}} U(\mathbf{z}, \mathbf{y})$
 $\exists \mathbf{x}$ s.t. constraints($\mathbf{x}, \mathbf{y}, \mathbf{z}$) hold

JTK



find \mathbf{x}
s.t. constraints($\mathbf{x}, \mathbf{y}^*, \mathbf{z}^*$) hold

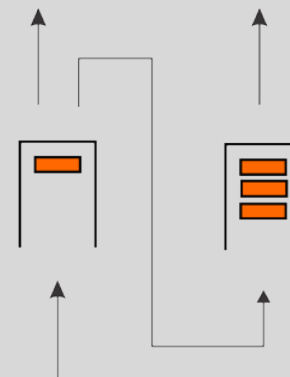
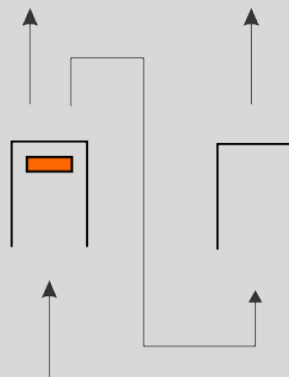
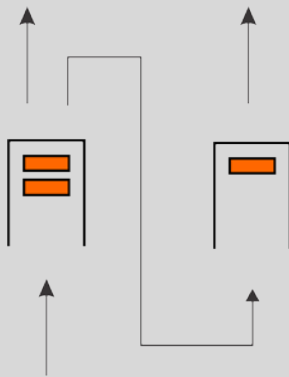
JTC

back to the queueing problem

$$L_n(t+1) = L_n(t) + W_n(t) - \mu_n^{(1)}(t) - \mu_n^{(3)}(t)$$

$$\hat{L}_n(t+1) = \hat{L}_n(t) + \mu_n^{(3)}(t) - \mu_n^{(2)}(t)$$

Obtained from OJS



We represent the policy for determining the schedule by a pair (ALG, u)

Use a queue-length based utility function

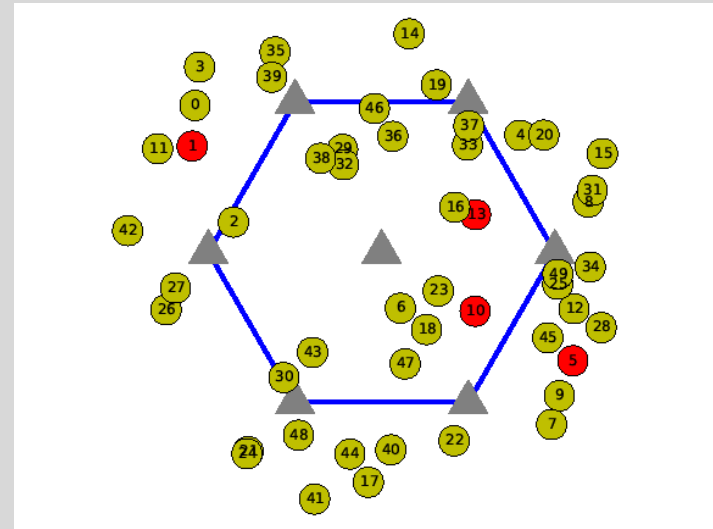
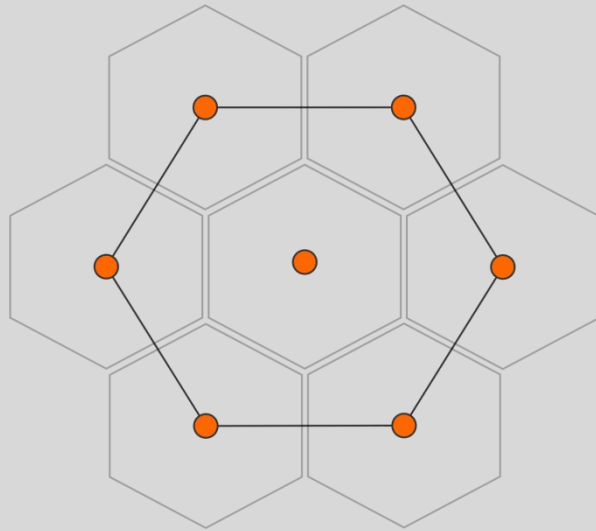
$$u_Q(i, r) = \begin{cases} L_{n(i)} p(i, r), & r = 1, \\ \max\{L_{n(i)} - \hat{L}_{n(i)}, 0\}, & r = 0, \end{cases}$$

Theorem

Policy $(\text{OJS} - \text{OPT}, u_Q)$ is throughput-optimal

throughput with approximation algorithms

In order to evaluate performance in the case **without optimal algorithms**, use **simulations**

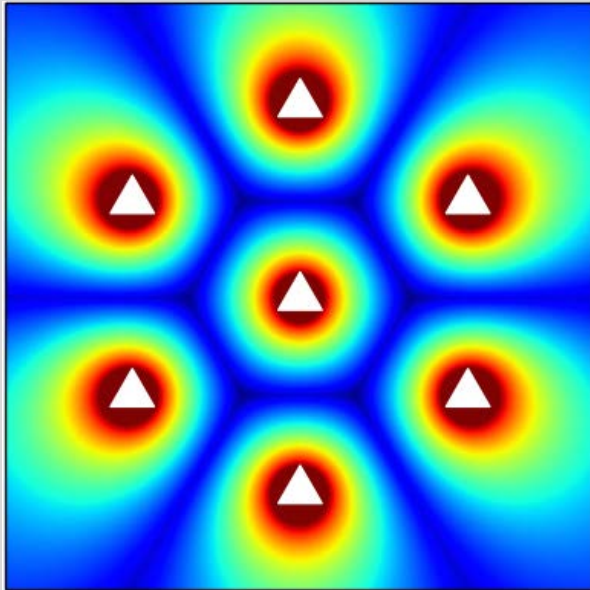


This also allows use detailed physical layer:

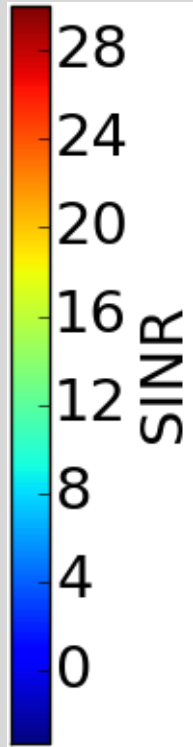
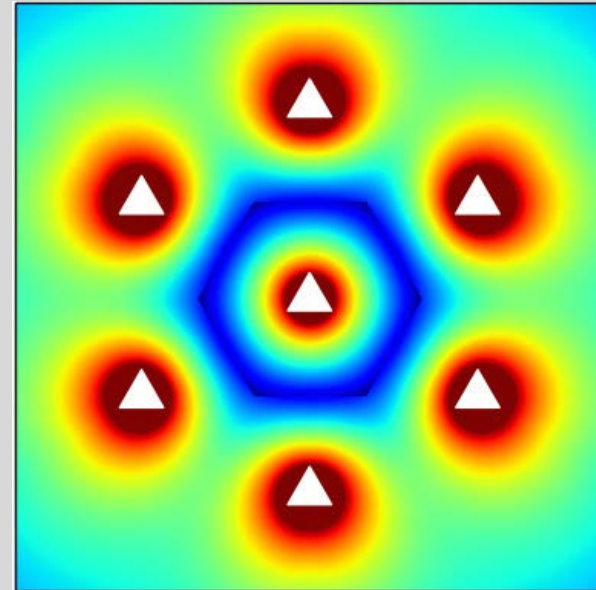
- Hata propagation model
- packets of **73b**
- **7** base stations **700m** apart
- **$S = 50$** scheduled blocks
- **$N = 50$** users

In order to evaluate performance in the case **without optimal algorithms**, use **simulations**

single-transmission

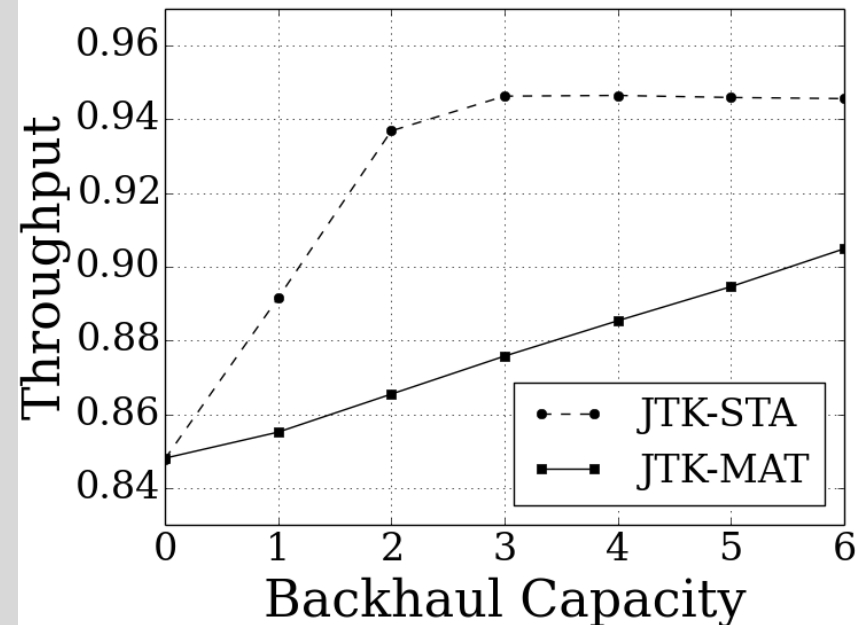
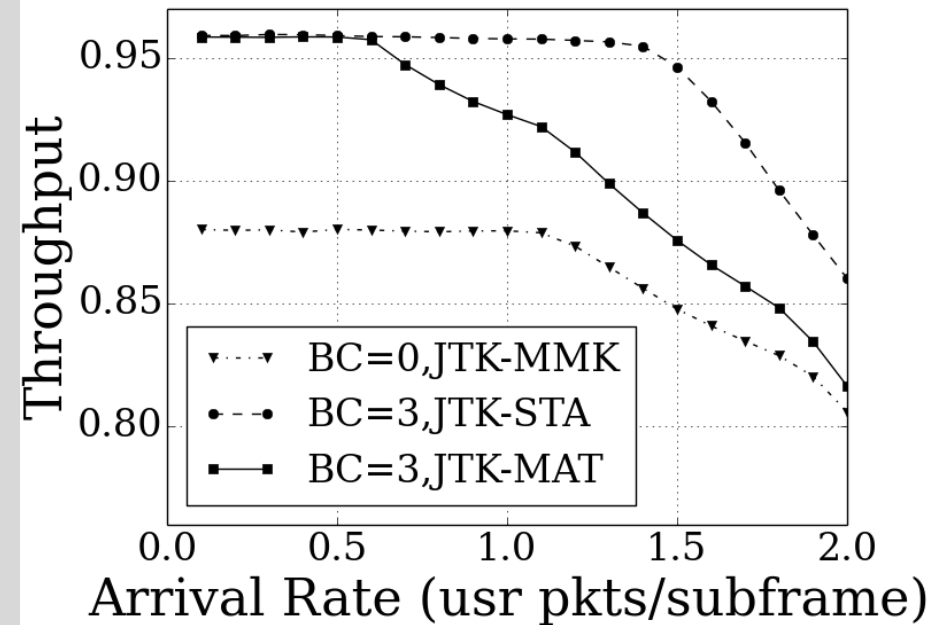


joint-transmission



This also allows use detailed physical layer:

- Hata propagation model
- packets of 73b
- 7 base stations 700m apart
- $S = 50$ scheduled blocks
- $N = 50$ users



Two **observations** from simulations:

- bulk of **gains from CoMP** can be obtained with **small backhaul**
- increase throughput cell-edge users with only minor cost to other users

Conclusions and outlook

Performance analysis and scheduling of cellular networks with joint-transmission

- derive **approximation algorithms** to determine per-slot schedule
- look at evolution of **queueing** model given this schedule

This can be used for designing backhaul networks:

- between **which BSs**, **what capacity**?

Question: how does the approximation algorithm affect the stability region?