Optimization of Base Station Antenna Directivity for Base Station Cooperation Cellular Systems

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- System model
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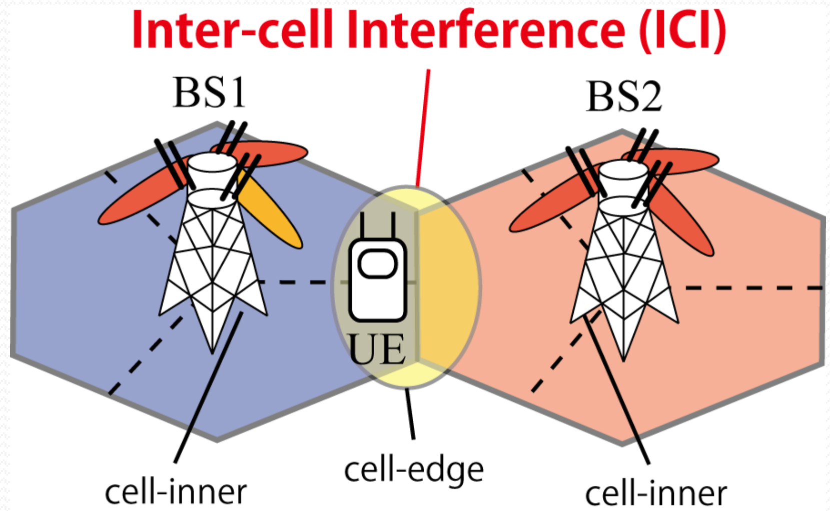
- Numerical analysis
- Conclusion

Background

◆Single transmission

✓ **Capacity at the cell-edge is degraded**

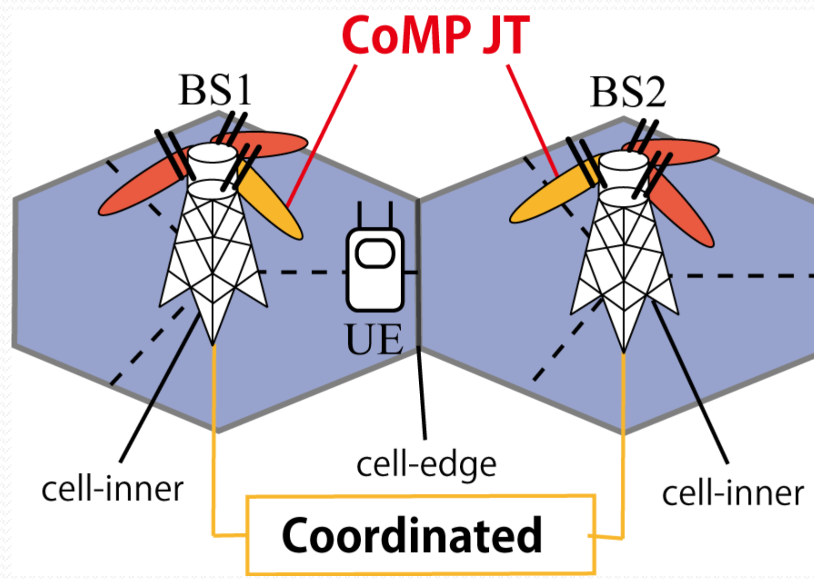
- **pathloss**
- **Inter-cell interference (ICI)**
- **antenna correlation**



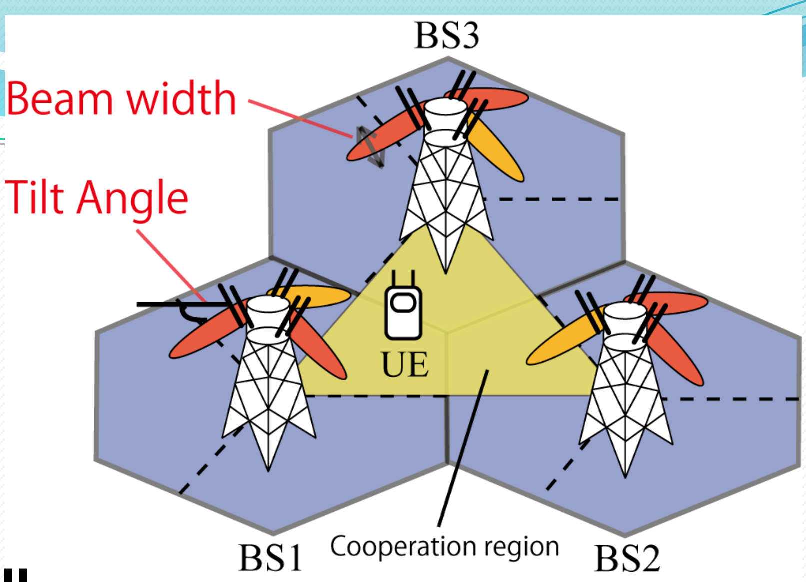
◆Base station cooperation (BSC)

✓ **Capacity at the cell-edge is improved**

- **CoMP JT**
- **transmit signal to control ICI**



Background



◆Base station antenna directivity

- Single transmission

Maximize the received power of own cell
To reduce the ICI, minimize the power to adjacent cell

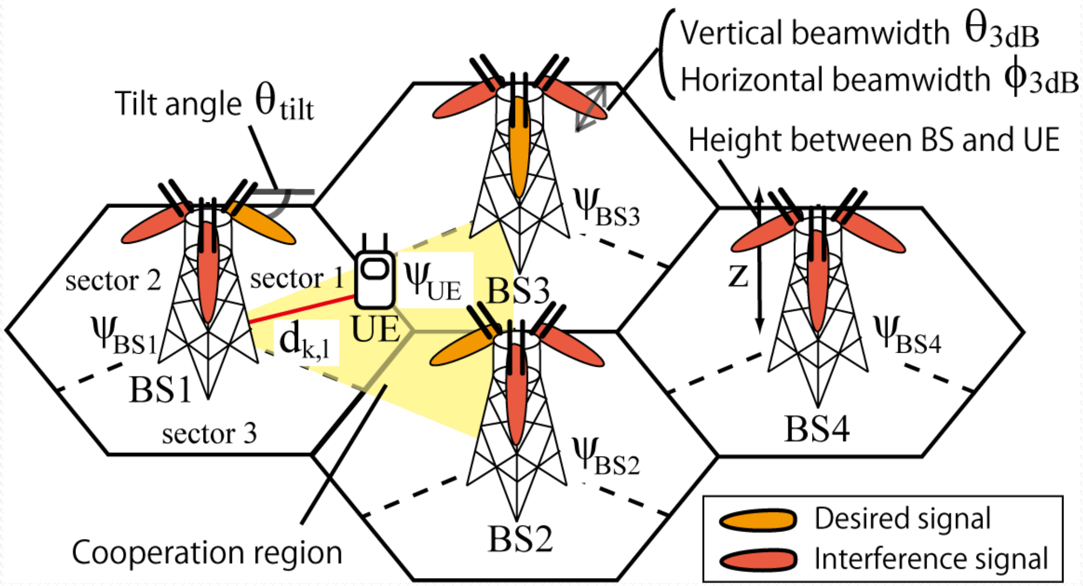
- Base station cooperation

Maximize the received of cooperative cell without the problem of ICI

Base station antenna directivity is required to be designed differently from conventional way

Optimize base station antenna directivity

Base station cooperation system



System model	
The number of cooperative BSs K_{BS}	3
The number of BS antennas N_{BS}	2
The number of UE per sector K_{UE}	1
The number of UE antennas N_{UE}	2

- **Received signal**

$$\mathbf{y} = \mathbf{H}_{1,1}\tilde{\mathbf{s}}_{1,1} + \mathbf{H}_{2,2}\tilde{\mathbf{s}}_{2,2} + \mathbf{H}_{3,3}\tilde{\mathbf{s}}_{3,3} + \sum_{\substack{(k,l)\neq(1,1),\\(2,2),(3,3)}}^{\text{non-cooperative}} \mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \mathbf{n}$$

BS sector

$$= \begin{bmatrix}\mathbf{H}_{1,1} & \mathbf{H}_{2,2} & \mathbf{H}_{3,3}\end{bmatrix} \begin{bmatrix}\tilde{\mathbf{s}}_{1,1} \\ \tilde{\mathbf{s}}_{2,2} \\ \tilde{\mathbf{s}}_{3,3}\end{bmatrix} + \sum^{\text{non-cooperative}} \mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \mathbf{n}$$

$$= \mathbf{H}\tilde{\mathbf{s}} + \sum^{\text{non-cooperative}} \mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \mathbf{n}$$

Desired signal **Interference** **Noise**

- **Channel Matrix**

Evaluation angle Azimuth angle

$$\mathbf{H}_{k,l} = \sqrt{\beta_{k,l}}\,\mathbf{H}^{iid}_{k,l} A_{k,l}(\theta,\phi)$$

pathloss $\beta_{k,l} = \alpha \cdot \sqrt{d_{k,l}^2 + z^2}^{\,-m}$

Channel matrix with independent and identically distributed elements $\mathbf{H}^{iid}_{k,l}$

Base station antenna directivity $A_{k,l}(\theta,\phi)$

Distance between BS and UE $d_{k,l} = |\psi_{UE} - \psi_{BSk}|$

Instantaneous capacity

- **Singular Value Decomposition**

$$\mathbf{y} = \underline{\mathbf{H}}\tilde{\mathbf{s}} + \sum^{\text{non-cooperative}} \mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \mathbf{n} = \left(\underline{\mathbf{U}\Lambda\mathbf{V}^H}\right)\tilde{\mathbf{s}} + \sum^{\text{non-cooperative}} \mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \mathbf{n}$$

$$\tilde{\mathbf{y}} = \mathbf{U}^H\mathbf{y}$$

$$= \mathbf{U}^H(\mathbf{U}\Lambda\mathbf{V}^H)(\mathbf{V}\mathbf{s}) + \sum^{\text{non-cooperative}} \mathbf{U}^H\mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \mathbf{U}^H\mathbf{n}$$

$$= \Lambda\mathbf{s} + \sum^{\text{non-cooperative}} \mathbf{U}^H\mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \tilde{\mathbf{n}}$$

Precoding	$\tilde{\mathbf{s}} = \mathbf{V}\mathbf{s}$
Postcoding	$\tilde{\mathbf{y}} = \mathbf{U}^H\mathbf{y}$
Eigen matrix	Λ

Transmit power per BS	$P_{\text{BS}} = \mathrm{E}[\tilde{\mathbf{s}}_{k,l}^H\tilde{\mathbf{s}}_{k,l}]$
Total transmit power	$P = K_{\text{BS}}P_{\text{BS}}$
Transmit power per stream	$P_{\text{S}} = P/q$
Noise power	P_{n}
The number of streams	$q = \min(K_{\text{BS}}N_{\text{BS}}, K_{\text{UE}}N_{\text{UE}})$

- **Received signal (*i-th eigenmode*)**

$$\tilde{y}_i = \sqrt{\lambda_i}s_i + \sum^{\text{non-cooperative}} \mathbf{U}_i^H\mathbf{H}_{k,l}\tilde{\mathbf{s}}_{k,l} + \tilde{n}_i$$

- **Received SINR (*i-th eigenmode*)**

$$\gamma_i = \lambda_i \frac{P_{\text{S}}}{\sum^{\text{non-cooperative}} \|\mathbf{U}_i^H\mathbf{H}_{k,l}\|^2 P_{\text{BS}} + P_{\text{n}}}$$

- **Instantaneous capacity** (*i-th eigenmode*)

$$C_i = \log_2(1+\gamma_i)$$

Average channel capacity

Instantaneous channel capacity
(i-th eigenmode)

$$C_i = \log_2(1+\gamma_i)$$

PDF of each eigenvalue: $f_i(\lambda_i)$

- **Average channel capacity**

$$\bar{C}(\psi_{\mathrm{UE}}, A(\theta,\phi)) = \sum_{i=1}^{q} \int_0^{\infty} C_i \cdot f_i(\lambda_i) d\lambda_i$$

- Eigenvalue Theory of Wishart Matrix

◆ BSC-MIMO (3,2)×(1,2) system <----------- $(K_{\mathrm{BS}}, N_{\mathrm{BS}}) \times (K_{\mathrm{UE}}, N_{\mathrm{UE}})$

K_{BS}: The number of BSs
N_{BS}: The number of BS antennas
K_{UE}: The number of UEs
N_{UE}: The number of UE antennas

- PDF of 1st eigen mode

$$f_1(\lambda_1) = \sum_{\substack{\{k,l,m\,|\,(k,l,m)=\\(1,2,3),(2,3,1),(3,1,2)\}}} \frac{\sigma_k e^{-\frac{\lambda_1}{\sigma_k}}}{(\sigma_k-\sigma_l)^3(\sigma_k-\sigma_m)^3}\Big[(\sigma_k-\sigma_l)(\sigma_k-\sigma_m)\lambda_1^2 - 2\{\sigma_k^3+(\sigma_l+\sigma_m)\sigma_k^2-(\sigma_l^2+3\sigma_l\sigma_m+\sigma_m^2)\sigma_k+\sigma_l\sigma_m(\sigma_l+\sigma_m)\}\lambda_1 + 2\sigma_k\{\sigma_k^3+(\sigma_l+\sigma_m)\sigma_k^2+(\sigma_l^2+\sigma_l\sigma_m+\sigma_m^2)\sigma_k-3\sigma_l\sigma_m(\sigma_l+\sigma_m)\}\Big] - f_2(\lambda_1)$$

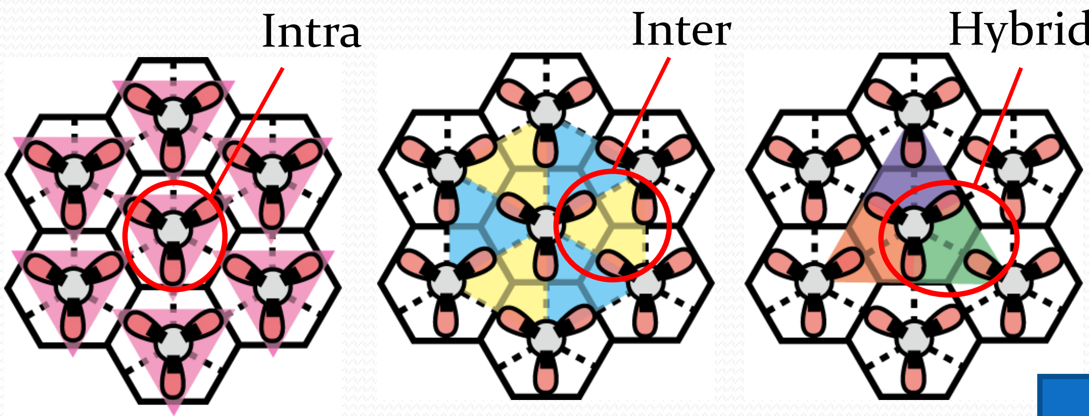
- PDF of 2nd eigen mode

$$f_2(\lambda_2) = \frac{1}{(\sigma_1-\sigma_2)^4(\sigma_2-\sigma_3)^4(\sigma_3-\sigma_1)^4}\cdot\Bigg[\sum_{\substack{\{k,l,m\,|\,(k,l,m)=\\(1,2,3),(2,3,1),(3,1,2)\}}} 2\sigma_k^7(\sigma_l-\sigma_m)^4\cdot e^{-\frac{2\lambda_2}{\sigma_k}} - \sigma_k\sigma_l(\sigma_k-\sigma_m)(\sigma_l-\sigma_m)\cdot e^{-\left(\frac{1}{\sigma_k}+\frac{1}{\sigma_l}\right)\lambda_2}\Big[(\sigma_k-\sigma_l)^2(\sigma_k+\sigma_l)(\sigma_k-\sigma_m)(\sigma_l-\sigma_m)\lambda_2^2 + 2(\sigma_k-\sigma_l)^2\{(2\sigma_k^2+3\sigma_k\sigma_l+2\sigma_l^2)\sigma_m^2-(\sigma_k+\sigma_l)(\sigma_k^2+3\sigma_k\sigma_l+\sigma_l^2)\sigma_m+\sigma_k\sigma_l(\sigma_k^2+\sigma_k\sigma_l+\sigma_l^2)\}\lambda_2 + 2\sigma_k\sigma_l\{(\sigma_k+\sigma_l)(6\sigma_k^2-11\sigma_k\sigma_l+6\sigma_l^2)\sigma_m^2-(3\sigma_k^4-\sigma_k^3\sigma_l-\sigma_k\sigma_l^3+3\sigma_l^4)\sigma_m+\sigma_k\sigma_l(\sigma_k^3+\sigma_l^3)\}\Big]\Bigg]$$

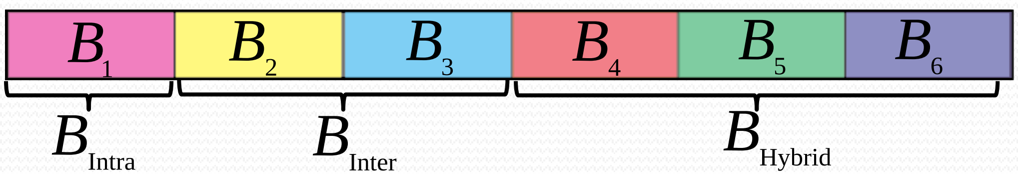
$\sigma_i = \left(\sqrt{\beta_i} A_i(\theta,\phi)\right)^2$: eigenvalue of correlation matrix $\mathbf{H}^H\mathbf{H}$

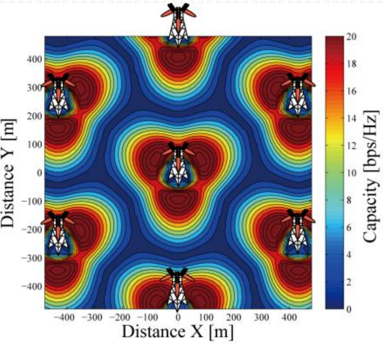
Objective function

Cooperative pattern (3GPP)

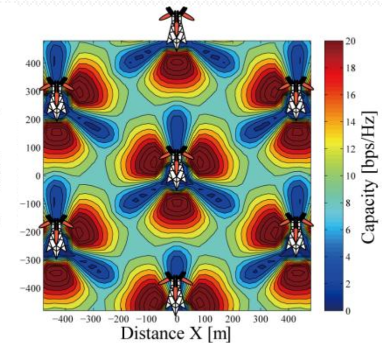


Resource

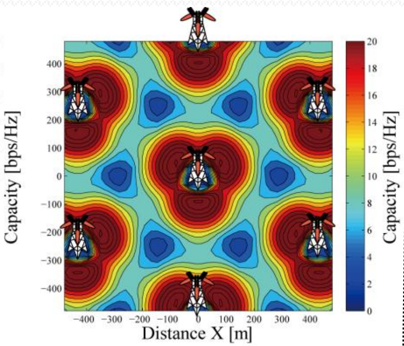




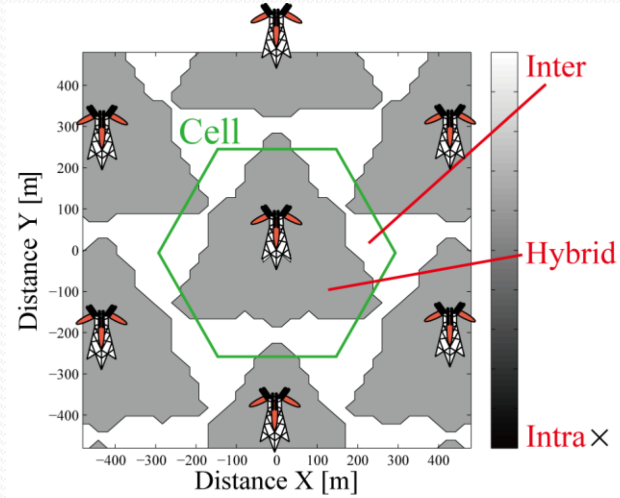
Intra C_{Intra}



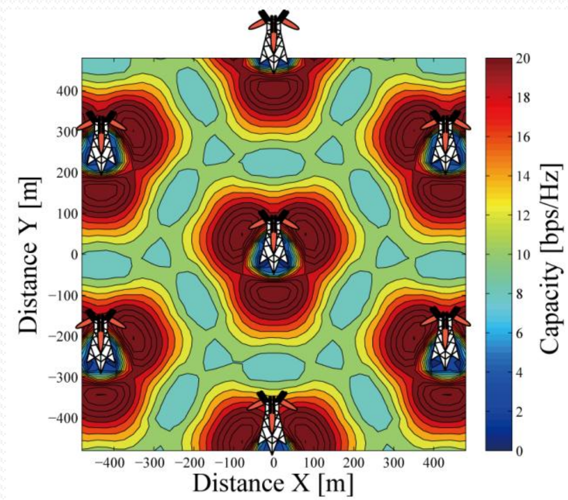
Inter C_{Inter}



Hybrid C_{Hybrid}



Cooperation region



BSC

$$\max(C_{\text{Intra}}, C_{\text{Inter}}, C_{\text{Hybrid}})$$

Objective function

- Resource (*i*-th cooperation)

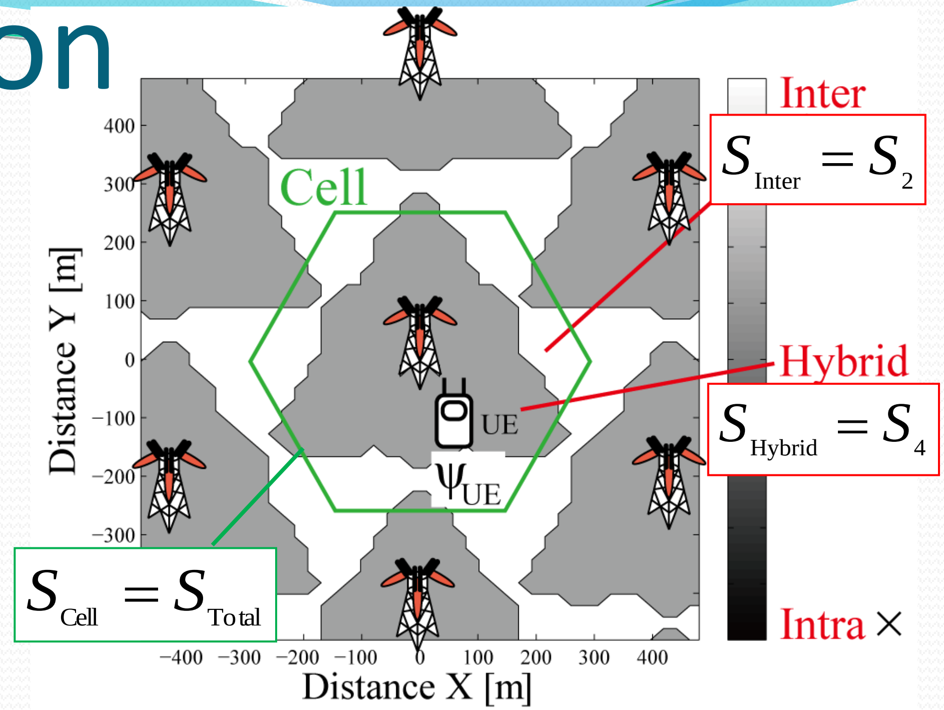
$$B_i = (S_i / S_{\mathrm{Total}}) B_{\mathrm{Total}}$$

- Average cell capacity (*i*-th cooperation)

$$C_i^{\Diamond} = \int_{S_i} \overline{C}(\psi_{\mathrm{UE}}, A(\theta,\phi))\,\mathrm{d}S / S_i$$

Average Cell Capacity (BSC)

$$C_{\mathrm{BSC}}^{\Diamond} = \sum_i \frac{B_i}{B_{\mathrm{Total}}} C_i^{\Diamond}$$



Cooperation region

- **optimal antenna directivity** $A^{\star}(\theta,\phi) = \arg\max_{A(\theta,\varphi)} C^{\Diamond}$

Assume that BS antenna directivity $A(\theta,\phi)$ as defined in 3GPP

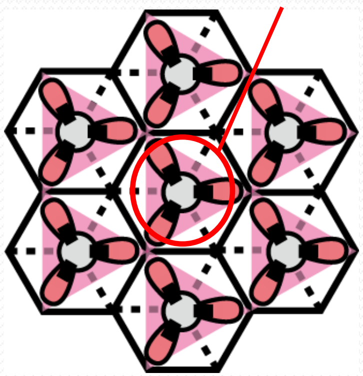
⬇

Maximize average cell capacity by varying the parameters

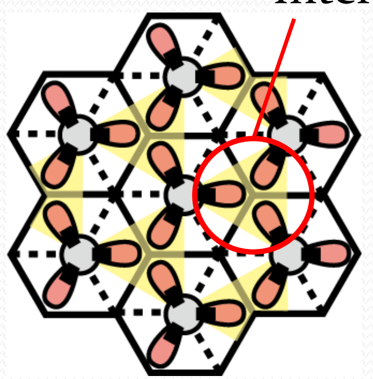
Objective function

Cooperative pattern (face to face)

Intra



Inter



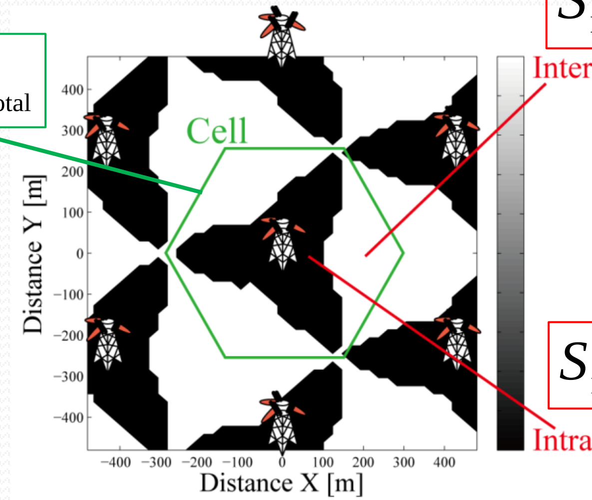
resource

B_1 | B_2

B_{Total}

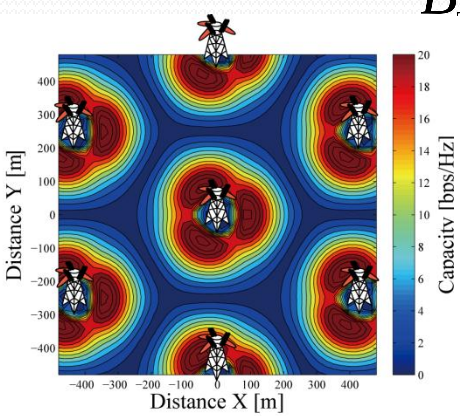
$S_{Cell} = S_{Total}$

$S_{Inter} = S_1$

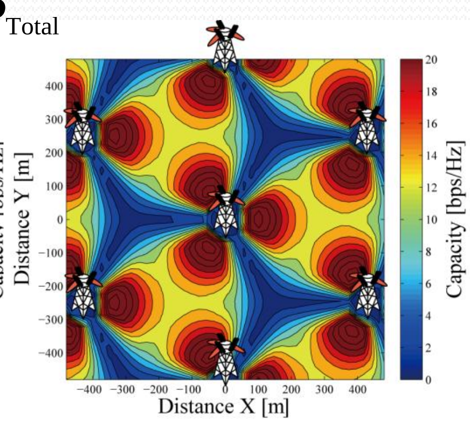


$S_{Intra} = S_2$

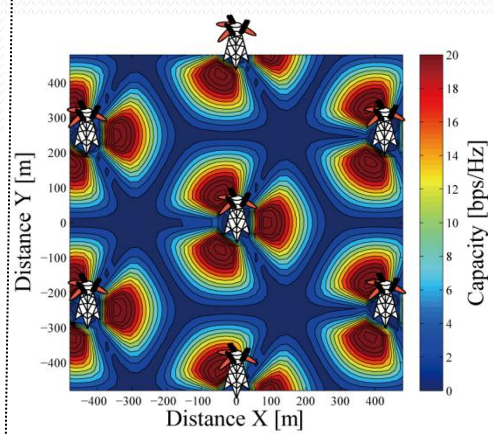
Cooperation region



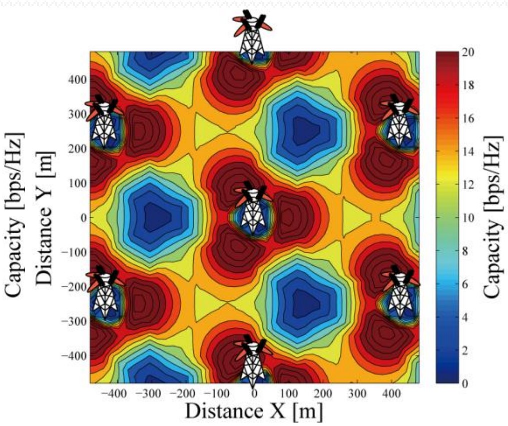
Intra C_{Inter}



Inter C_{Intra}



Single cell



BSC

$\max(C_{Intra}, C_{Inter})$

BS Antenna Directivity

- **3GPP Directivity**

$$A(\theta,\phi) = K_{\text{omni}} \cdot -\min\left[-\left[A_H(\phi) + A_V(\theta)\right], A_m\right]$$

Horizontal Directivity	$A_H(\phi) = -\min\left[12\left(\frac{\phi}{\phi_{3\text{dB}}}\right)^2, A_m\right]$	$A_m = 25\text{dB}$
Vertical Directivity	$A_V(\theta) = -\min\left[12\left(\frac{\theta-\theta_{\text{tilt}}}{\theta_{3\text{dB}}}\right)^2, SLA_V\right]$	$SLA_V = 20\text{dB}$

- **parameter**

θ_{tilt} **Vertical Tilt angle**

$\theta_{3\text{dB}}$ **Vertical Tilt angle**

$\phi_{3\text{dB}}$ **Horizontal beamwidth**

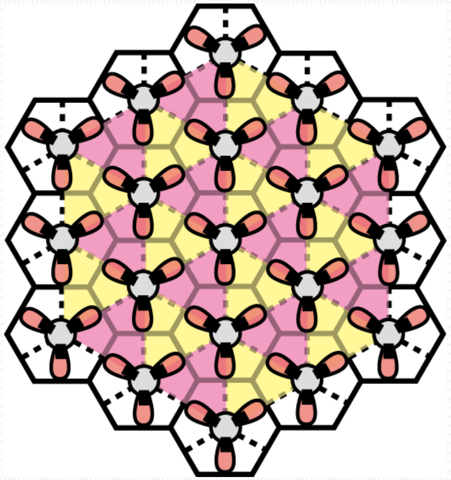
Derive parameters maximize average cell capacity

Numerical Analysis

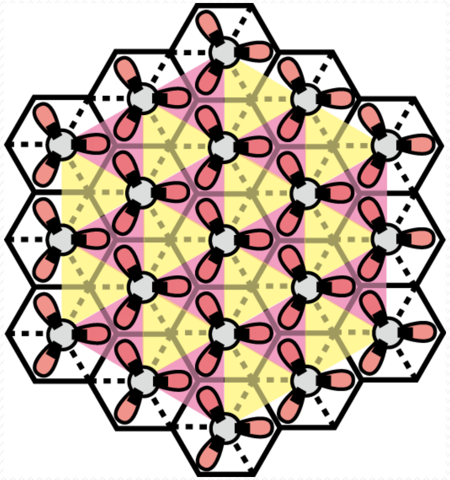
Numerical Condition	
The number of Cooperative BSs K_{BS}	3
The number of BS antennas N_{BS}	2
The number of UE per sector K_{UE}	1
The number of UE antennas N_{UE}	2
BS transmission power P_s	46dBm
Noise power P_n (10MHz Bandwidths)	-99dBm
Inter BS distance D	500m
Pathloss cofficient α	$10^{-3.45}$
Pathloss decay m	3.5
The height of antenna z	25m

- **19 cell model**

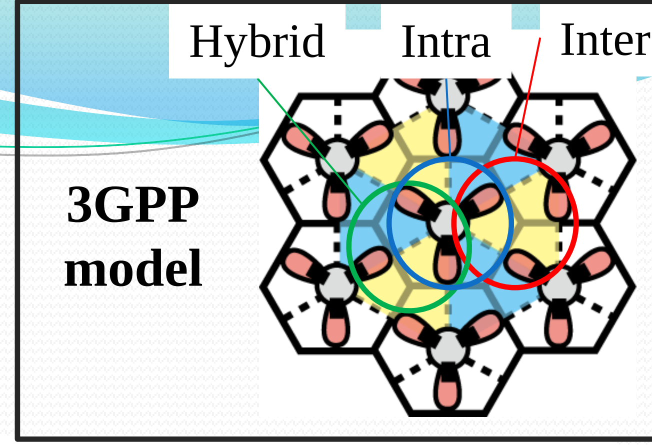
3GPP model



face to face model

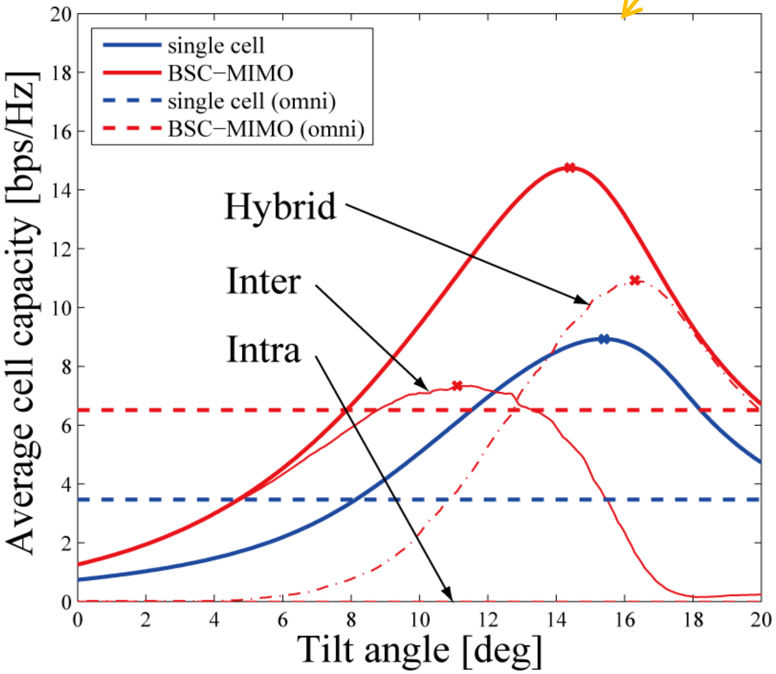


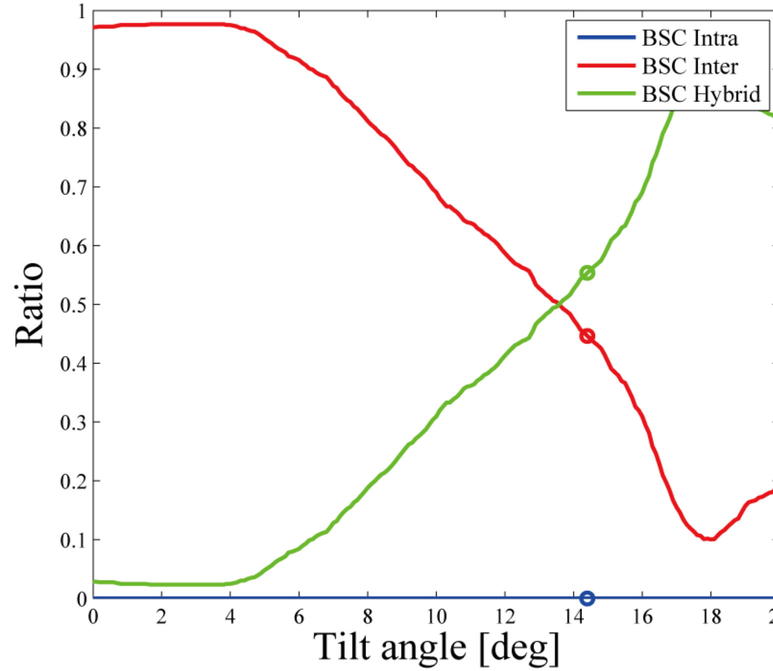
Optimal tilt angle θ_{tilt}



- **Average cell capacity**

$$\theta^{\star}_{\text{tilt}} = \arg\max_{\theta_{\text{tilt}}} C^{\Diamond}\left(\theta_{3\text{dB}} = 10\,\text{deg},\ \phi_{3\text{dB}} = 70\text{deg}\right)$$

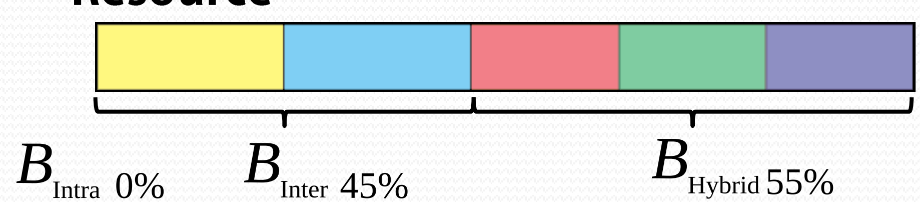




Optimal tilt angle

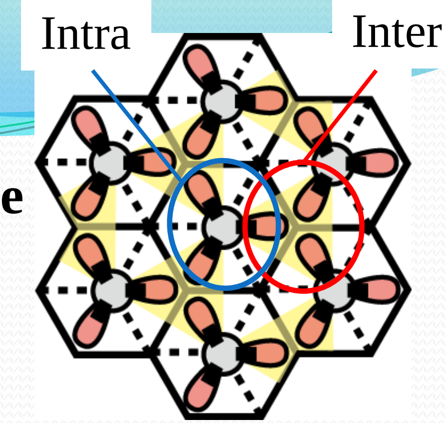
	Single cell	BSC-MIMO
θ_{tilt}	15.4deg	14.4deg

Resource



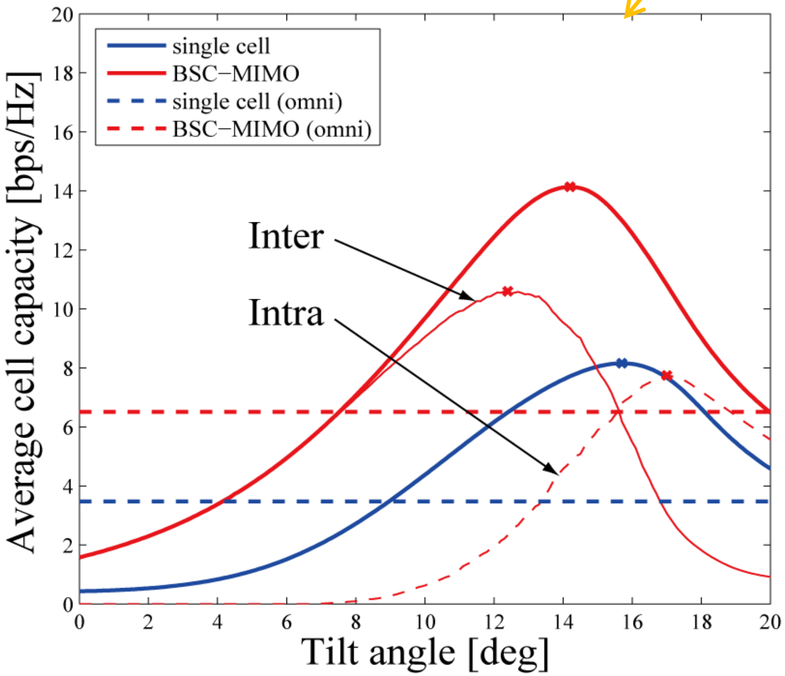
Optimal tilt angle θtilt

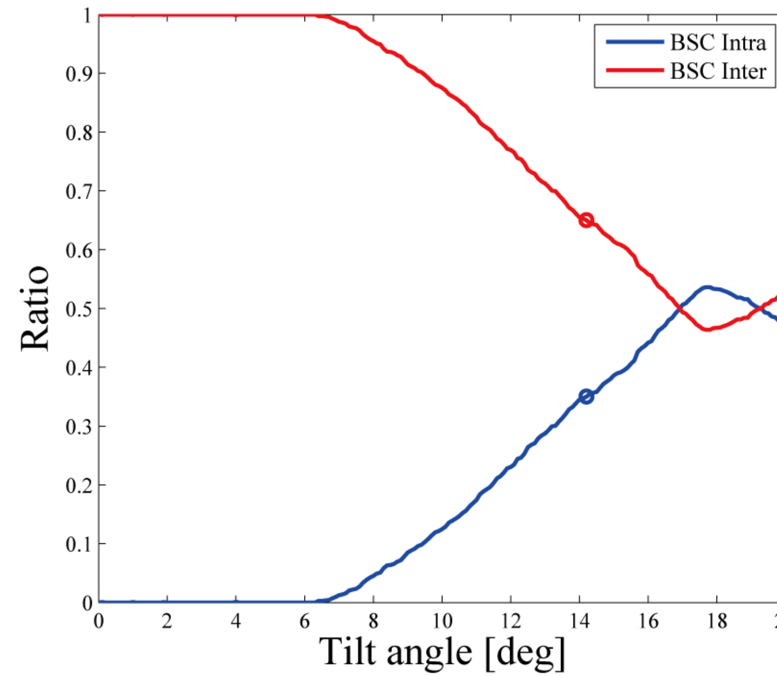
face to face model



- **Average cell capacity**

$$\theta^{\star}_{\text{tilt}} = \arg\max_{\theta_{\text{tilt}}} C^{\lozenge}\left(\theta_{3\text{dB}} = 10\,\text{deg},\ \phi_{3\text{dB}} = 70\text{deg}\right)$$

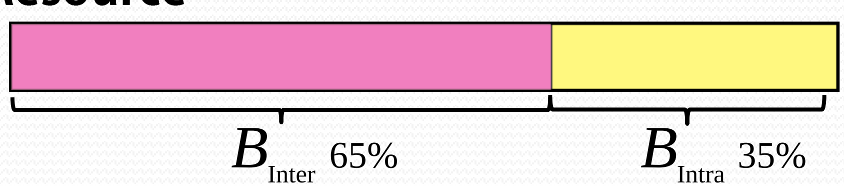




Optimal tilt angle

	Single cell	BSC-MIMO
θtilt	15.7deg	14.2deg

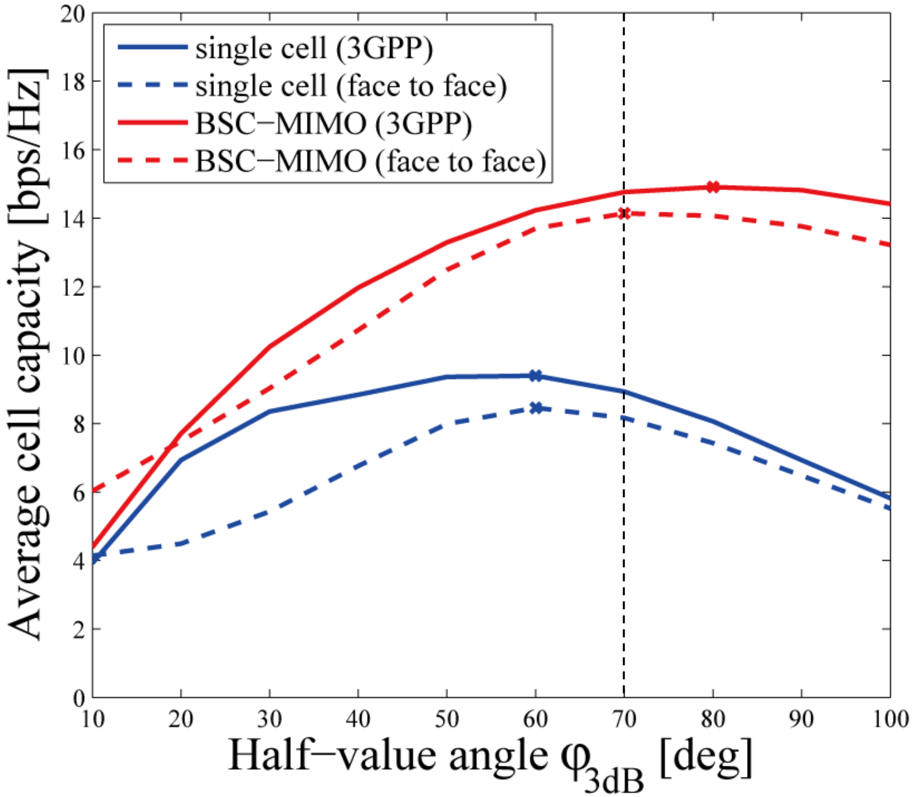
Resource



Horizontal beam width ϕ3dB

- **Average cell capacity**

$$\phi^{\star}_{3dB} = \arg\max_{\phi_{3dB}} C^{\Diamond}\left(\theta^{\star}_{tilt}, \theta_{3\delta B} = 10\,\deg\right)$$



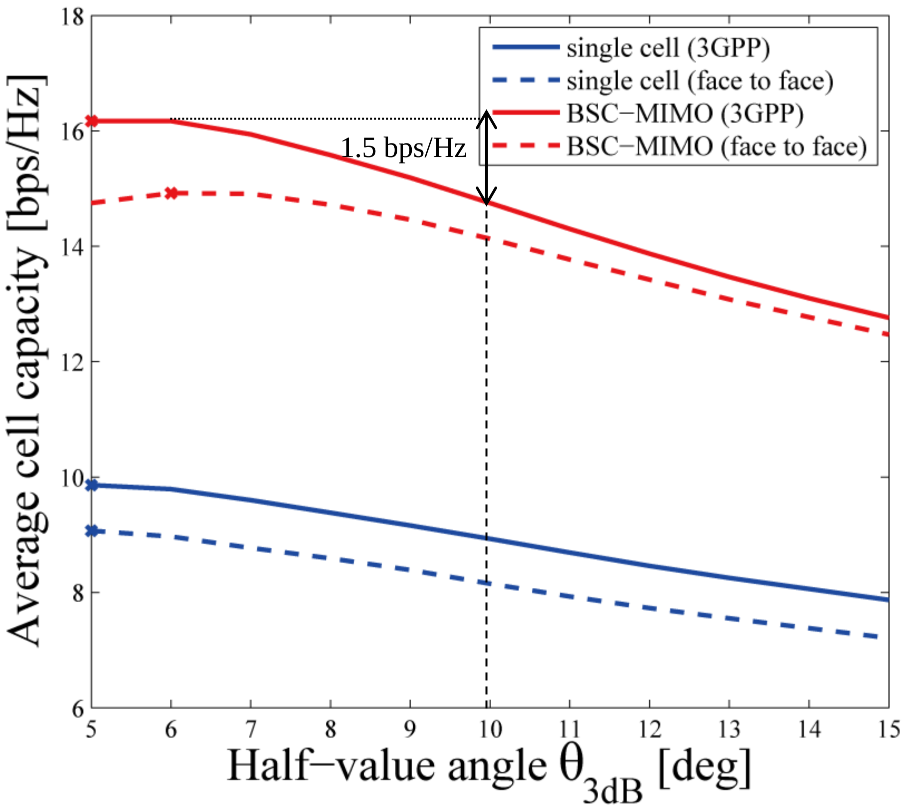
Optimal Horizontal Beamwidth

	Single cell	3GPP
ϕ 3dB	60deg	70deg
	BSC (3GPP)	BSC (face to face)
ϕ 3dB	80deg	70deg

Vertical beam width θ3dB

- **Average cell capacity**

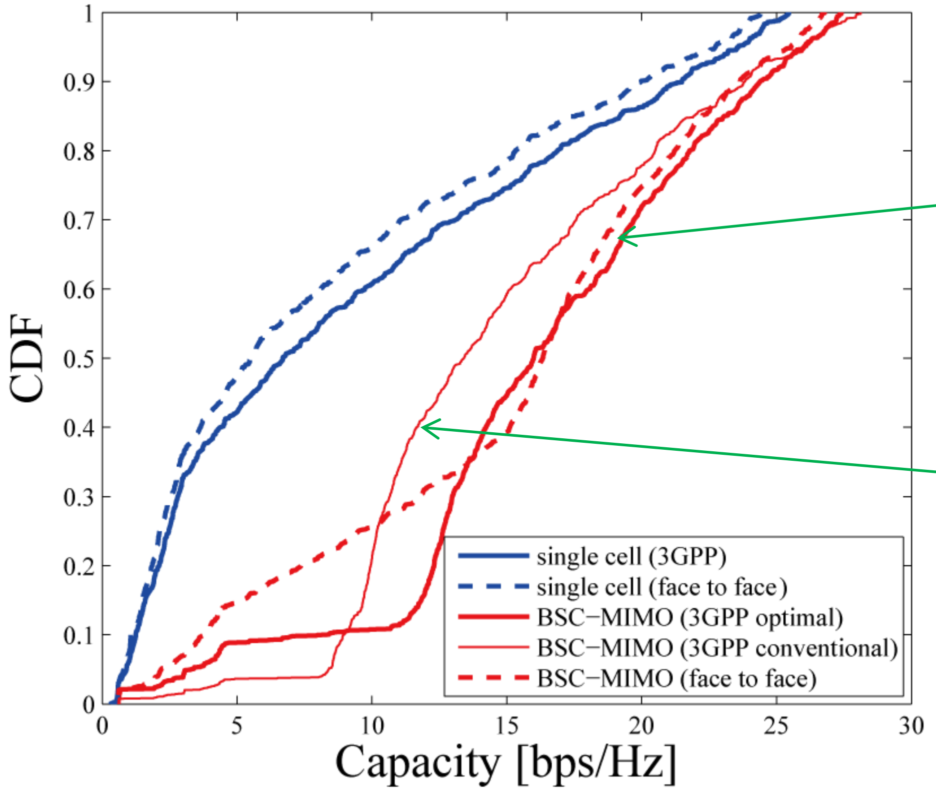
$$\theta^{\star}_{3\mathrm{dB}} = \arg\max_{\theta_{3\mathrm{dB}}} C^{\diamond}\left(\theta^{\star}_{\mathrm{tilt}}, \phi_{3\mathrm{dB}} = 70\,\mathrm{deg},\right)$$

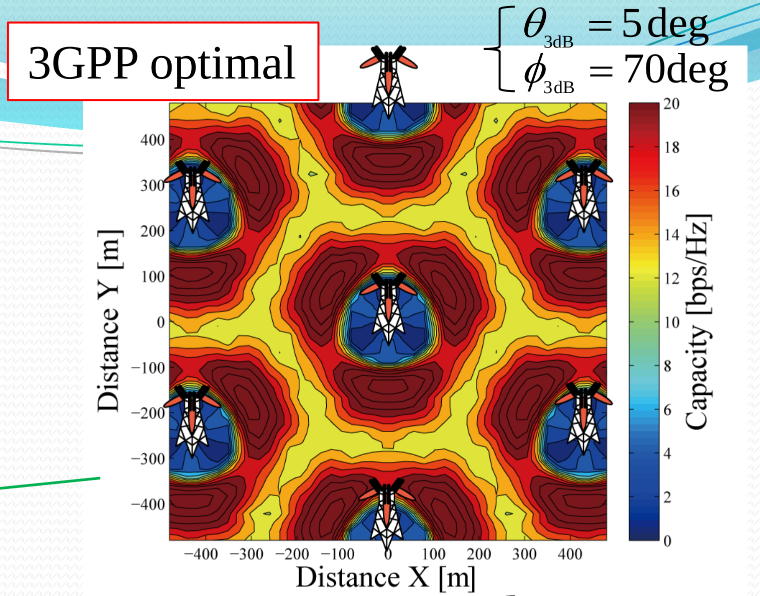


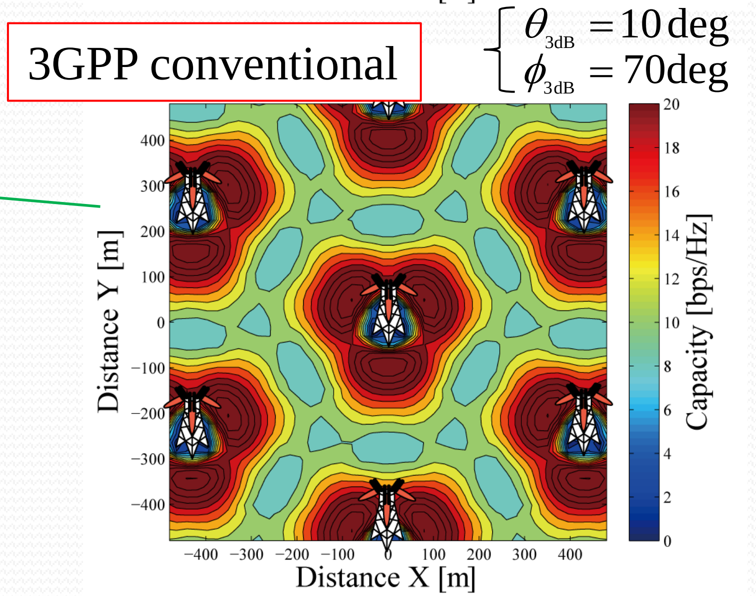
Optimal Vertical Beamwidth

	Single cell	3GPP
θ 3dB	5deg	10deg
	BSC (3GPP)	BSC (face to face)
θ 3dB	5deg	6deg

CDF of capacity



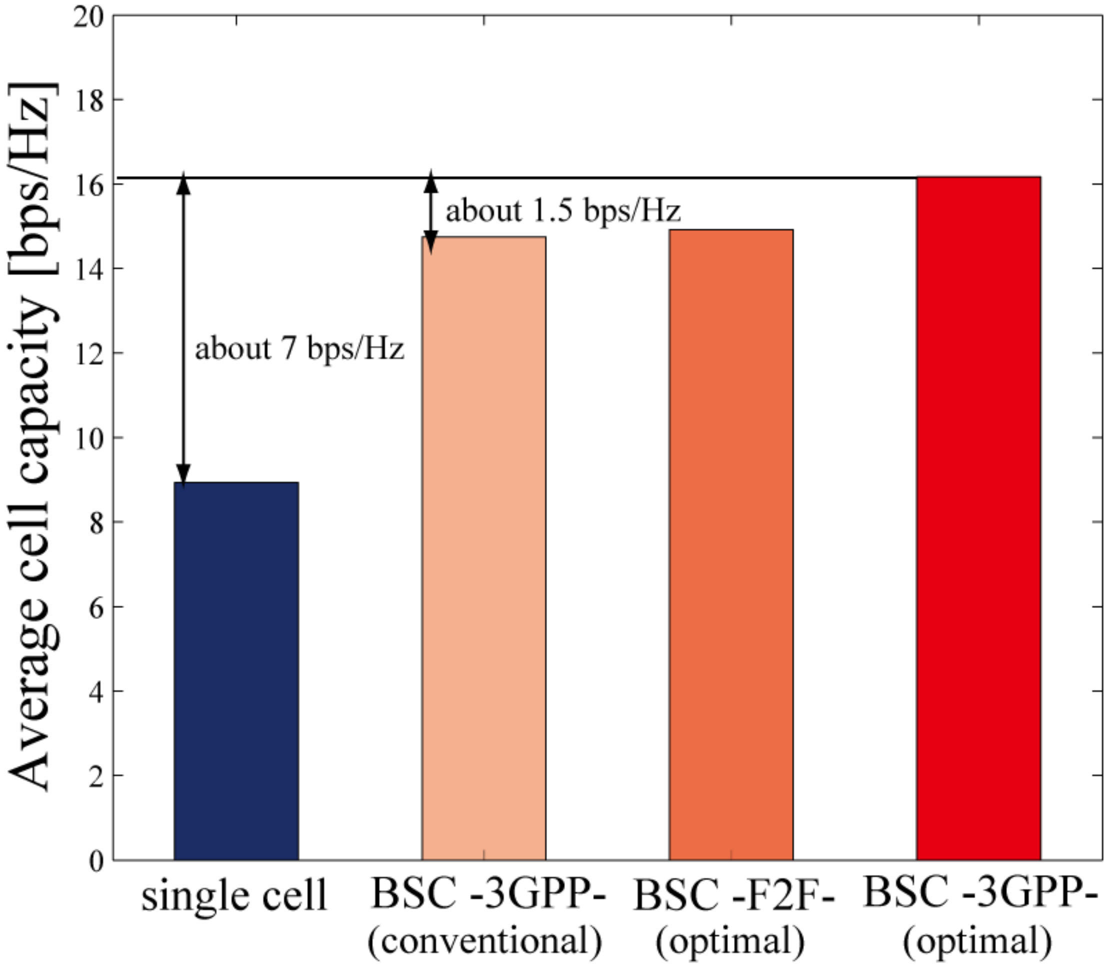




5% outage capacity

	Single cell (3GPP)	BSC-MIMO (face to face)	BSC-MIMO (3GPP optimal)	BSC-MIMO (3GPP conventional)
Capacity [bps/Hz]	0.895	2.196	3.291	8.398

Average cell capacity



$$\begin{cases} \theta_{3dB} = 10\,\text{deg} \\ \phi_{3dB} = 70\text{deg} \end{cases}$$

$$\begin{cases} \theta_{3dB} = 5\,\text{deg} \\ \phi_{3dB} = 70\text{deg} \end{cases}$$

Conclusion

- The optimal tilt angle of BSC-MIMO is smaller than that of single cell transmission
- Average cell capacity of BSC is increased about 1.5 bps/Hz by optimizing base station antenna directivity
- Average cell capacity of BSC system is increased about 7 bps/Hz than that of single cell