Cell-Edge-Aware Precoding for Downlink Massive MIMO Cellular Networks

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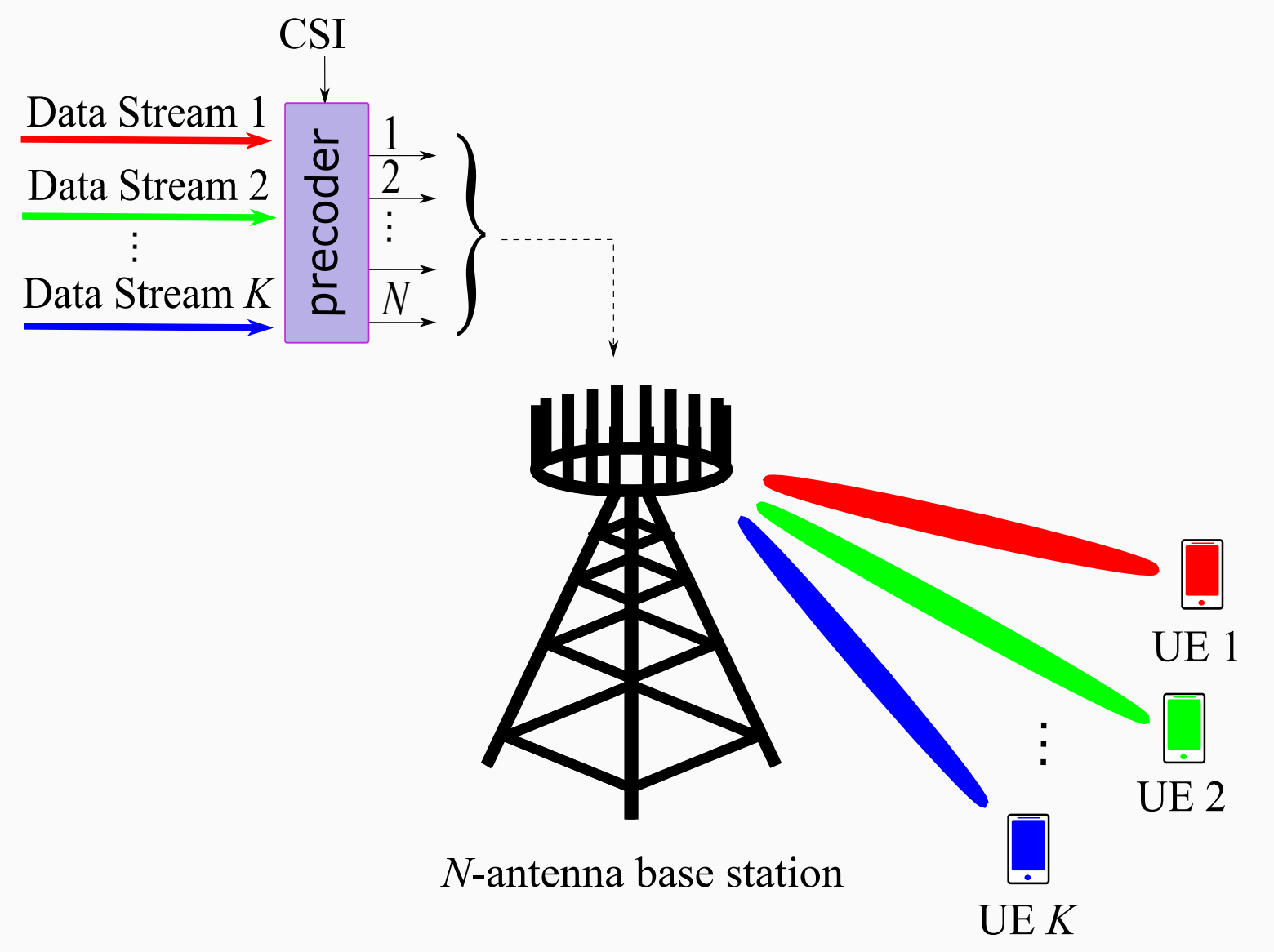
Introduction

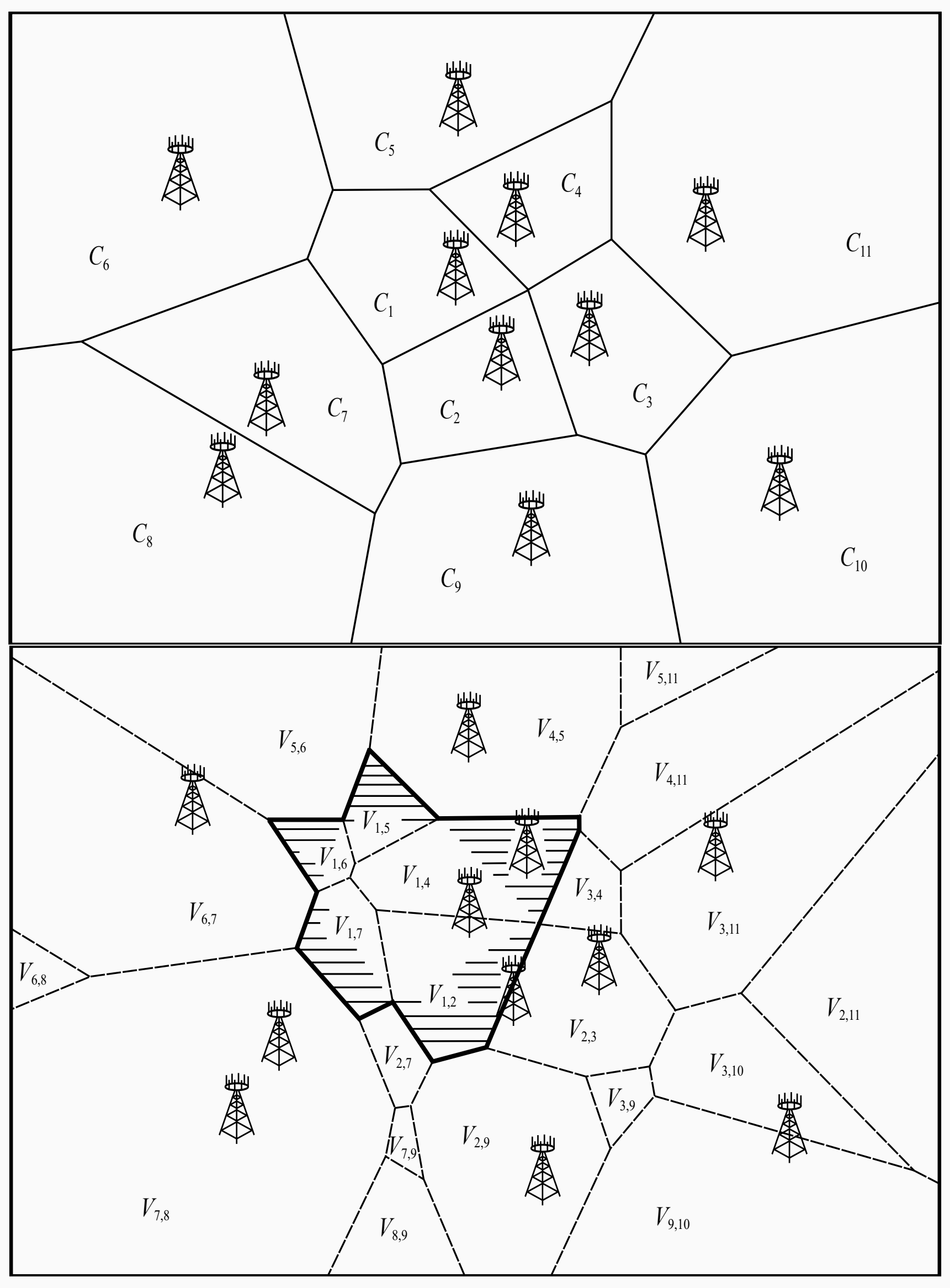
Motivation



- Massive MIMO: key enabling technology to achieve 5G requirements
- Inter-cell interference becomes key capacity limiting factor, especially for users located at the cell-edge
- Large antenna array can be used for not only spatial multiplexing, but also inter-cell interference suppression

Problem statement: In a downlink massive MIMO cellular network, if every BS utilizes some spatial dimensions to suppress inter-cell interference at the cell-edge neighboring UEs, is it possible to improve the network performance?

Network Structure



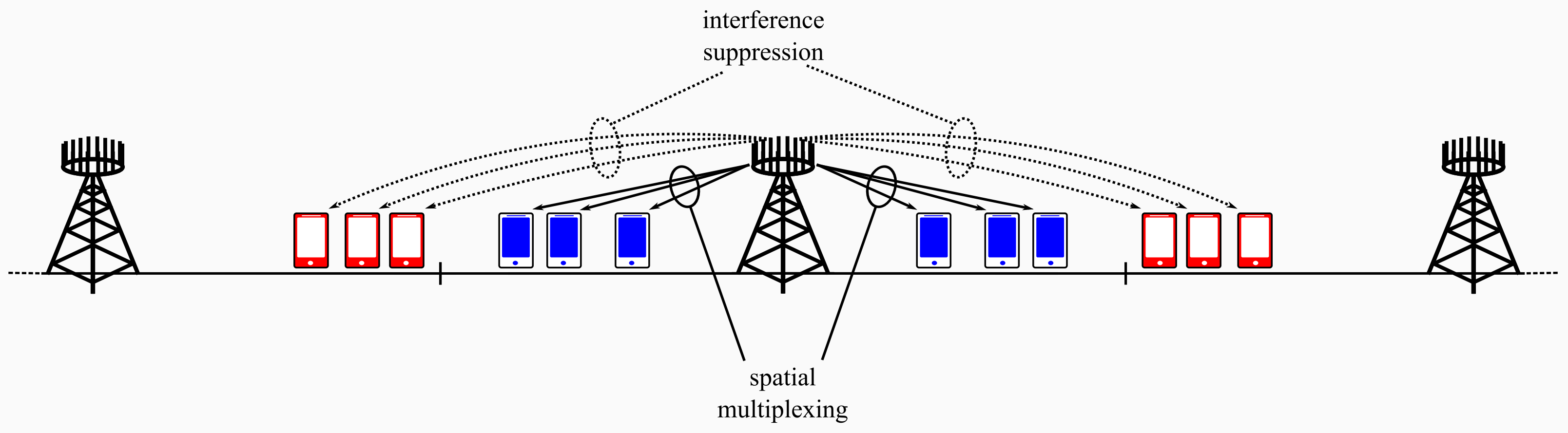
- BSs distributed as homogeneous PPP with spatial density λ_b, each equipped with N antennas and serves K UEs
- Second-order Voronoi tessellation: regions that UEs located inside associate with closest and second closest BSs
- Extended cell: $C_i^E = \cup_j V_{i,j}$, include (i) all UEs for which BS i is the closest, and (ii) all UEs for which BS i is the second closest.
- Channel estimations: the channel between BS i and UE k associated with BS j is

$$\mathbf{h}_{ijk} = \mathbf{x}_{ijk} / r_{ijk}^{\alpha},$$

r_{ijk} is the corresponding distance, α the path loss exponent, and $\mathbf{x}_{ijk}$ the small scale fading estimated by

$$\mathbf{x}_{ijk} = \sqrt{1-\tau_{ijk}^2}\hat{\mathbf{x}}_{ijk} + \tau_{ijk}\mathbf{q}_{ijk}$$

Downlink Transmission



Signal-to-interference ratio (SIR): from BS i to UE k, the SIR is given by

$$\gamma_{ik} = \frac{|\mathbf{h}_{iik}\mathbf{w}_{ik}|^2}{\sum_{l=1,l\neq k}^{K} |\mathbf{h}_{iik}\mathbf{w}_{il}|^2 + \sum_{j\neq i}\sum_{l=1}^{K} |\mathbf{h}_{jik}\mathbf{w}_{jl}|^2}$$

where the form of $\mathbf{w}_{ik}$ depends on the precoding scheme.

Precoding schemes

- Conventional Cell-Edge Unaware Zero Forcing (CEU-ZF) [1]:

$$\mathbf{w}_{\mathrm{u},ik} = \frac{1}{\sqrt{\zeta_{\mathrm{u},i}}}\left(\hat{\mathbf{H}}_i^{\mathrm{H}}\hat{\mathbf{H}}_i\right)^{-1}\hat{\mathbf{h}}_{iik}$$

- Proposed Cell-Edge Aware Zero Forcing (CEA-ZF):

$$\mathbf{w}_{\mathrm{a},ik} = \frac{1}{\sqrt{\zeta_{\mathrm{a},i}}}\left(\sum_{l=1}^{K}\hat{\mathbf{h}}_{iil}\hat{\mathbf{h}}_{iil}^{\mathrm{H}} + \sum_{l=1}^{K'}\hat{\mathbf{h}}_{i\bar{i}l}\hat{\mathbf{h}}_{i\bar{i}l}^{\mathrm{H}}\right)^{-1}\hat{\mathbf{h}}_{iik}$$

Coverage Probabilities

Theorem

The coverage probabilities under CEU-ZF and CEA-ZF are given as following

$$\mathbb{P}\left(\gamma_{\mathrm{u},ik} \geq \theta\right) = \frac{1}{\Gamma(\mu)}\int_0^{\infty}\Gamma\left(\mu, \frac{\mu}{\Omega}\left[\frac{(1-\tau^2)(1-\beta)Nr^{\alpha}}{\theta\left(\tau^2+\frac{2\pi\lambda r^2}{\alpha-2}\right)} - r^{\alpha}\right]^{\eta}\right) f_{\mathrm{c}}(r)dr$$

$$\mathbb{P}\left(\gamma_{\mathrm{a},ik} \geq \theta\right) = \int_0^{\infty}\int_t^{\infty}\Gamma\left(\mu, \frac{\mu}{\Omega}\left[\frac{(1-\tau^2)(1-2\beta)Ns^{\alpha}}{\theta\left(\bar{\tau}^2+\tau^2\frac{s^{\alpha}}{t^{\alpha}}+\frac{2\pi\lambda s^2}{\alpha-2}\right)} - t^{\alpha}\right]^{\eta}\right)\frac{f_{\mathrm{s|c}}(s,t)f_{\mathrm{c}}(t)}{\Gamma(\mu)}dsdt$$

Asymptotic results: large antenna array with perfect CSI

Corollary. When $\tau = \bar{\tau} = 0$, $\alpha = 4$, and $\beta = \frac{K}{N} \ll 1$, the coverage probabilities under CEU-ZF and CEA-ZF can be respectively approximated as

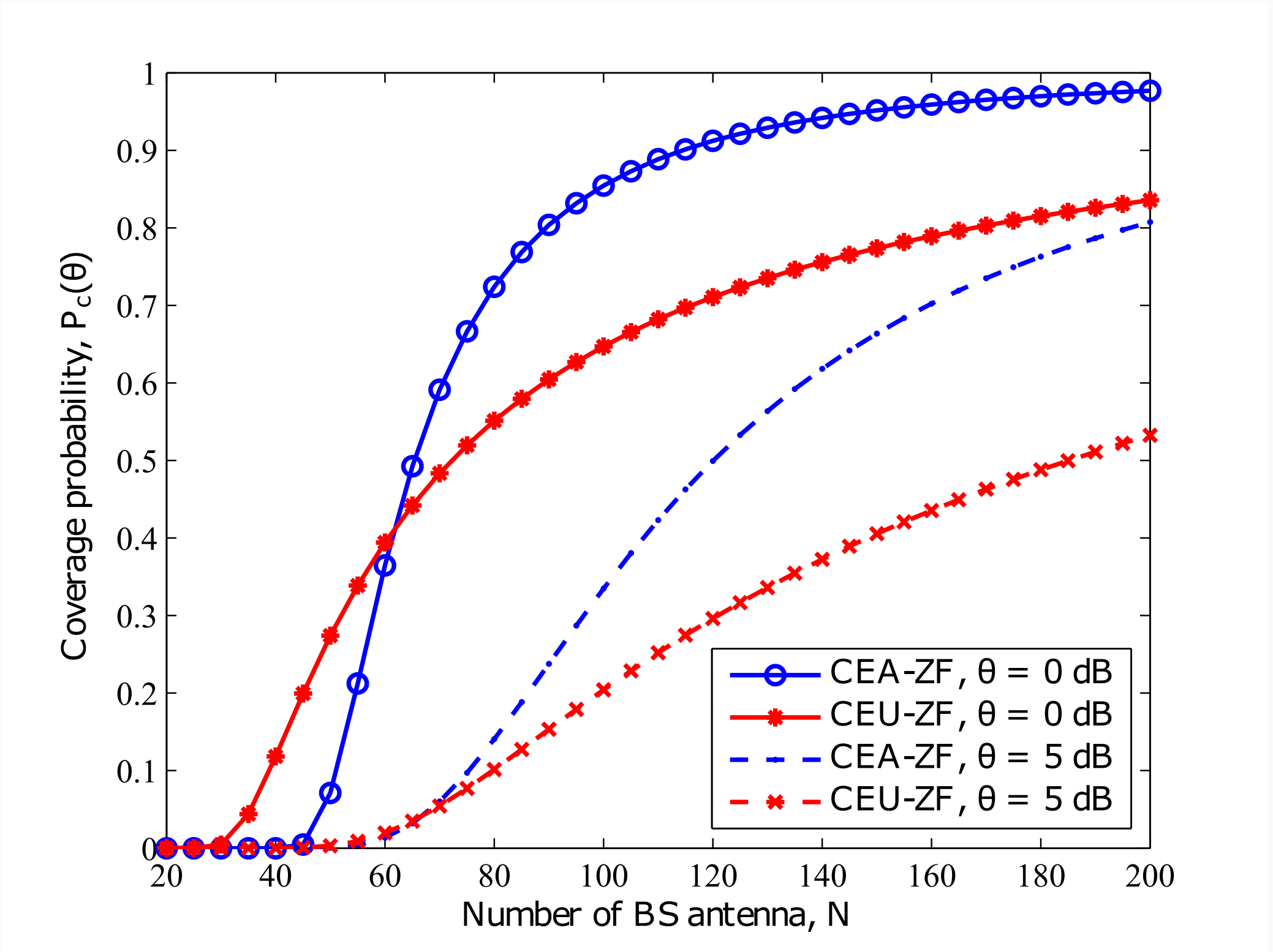
$$\mathbb{P}\left(\gamma_{\mathrm{u},ik} \geq \theta\right) \approx 1 - 2\beta\theta = 1 - \frac{2K\theta}{N},$$

$$\mathbb{P}\left(\gamma_{\mathrm{a},ik} \geq \theta\right) \approx 1 - (2\beta\theta)^2 = 1 - \frac{4K^2\theta^2}{N^2}.$$

Observations:

- CEA-ZF can achieve higher coverage probability than CEU-ZF when $N > 2\theta K$
- Outage probability of CEA-ZF and CEU-ZF decays as $1/N^2$ and $1/N$ respectively

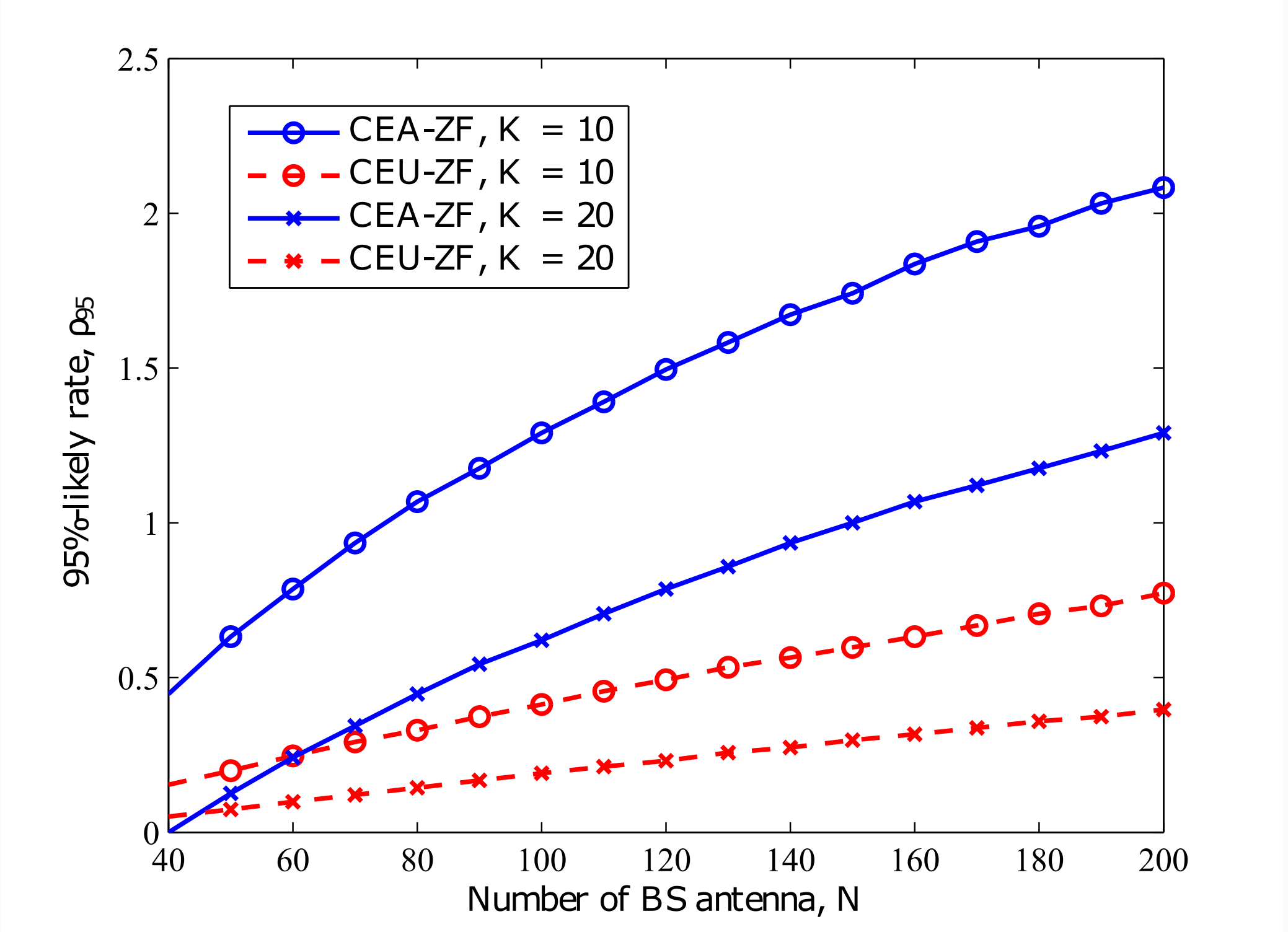
Numerical Results



Scenario parameters:
$\lambda_b = 10^{-6}\mathrm{m}^{-2}$, $K = 20$, $\alpha = 3.8$

Conclusive observations:

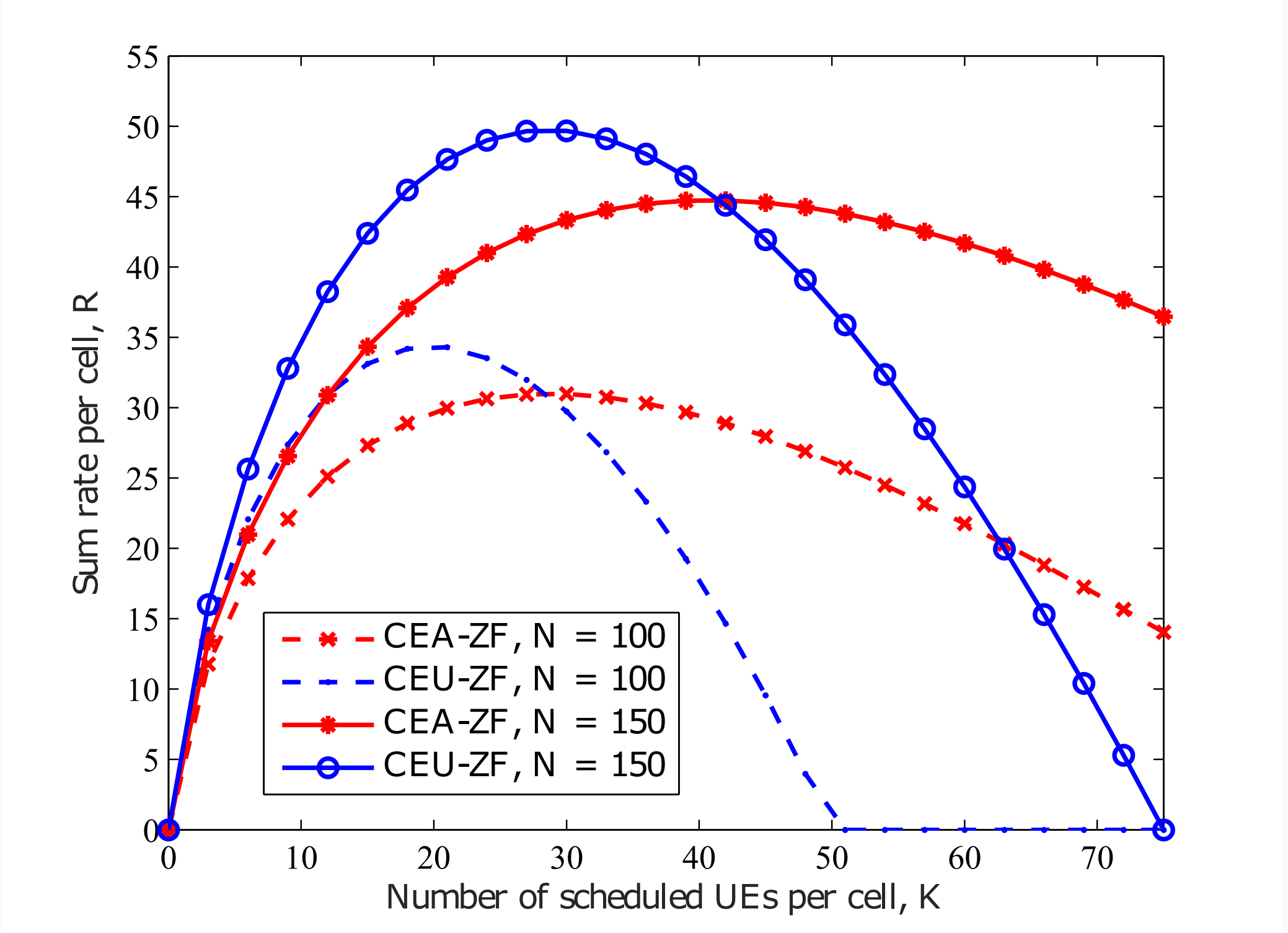
- CEA-ZF outperforms CEU-ZF only if the number of BS antennas exceeds a certain value
- As the number of BS antennas grows, the coverage probability under CEA-ZF converges to one much faster than that under CEU-ZF



Scenario parameters:
$\lambda_b = 10^{-6}\mathrm{m}^{-2}$, $\alpha = 3.8$

Conclusive observations:

- Both CEA-ZF and CEU-ZF benefit from a larger number of BS antennas N
- CEA-ZF precoder achieves a significantly larger 95%-likely rate, and the gain increases as N grows



Scenario parameters:
$\lambda_b = 10^{-6}\mathrm{m}^{-2}$, $\alpha = 3.8$

Conclusive observations:

- There exists optimal K that maximizes the sum rate for both CEU-ZF and CEA-ZF
- Under CEA-ZF, schedule less UEs and leave more DoF for cell-edge interference suppression
- CEA-ZF outperforms CEU-ZF in aggregated per cell rate

References

[1] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 461–471, Feb. 2004.