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Energy Efficiency Optimization In Cell-free Massive MIMO With Normalized Conjugate Beamforming

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Contents

1. Background

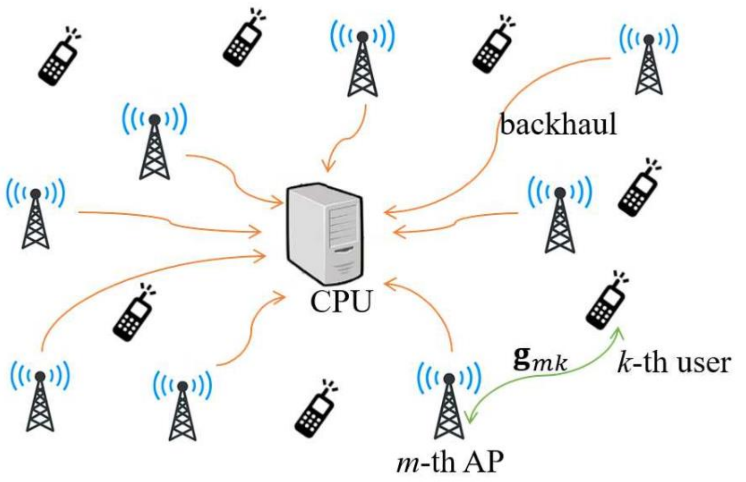
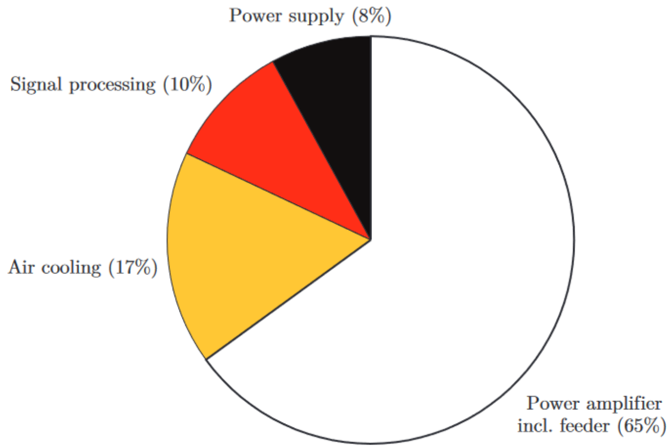


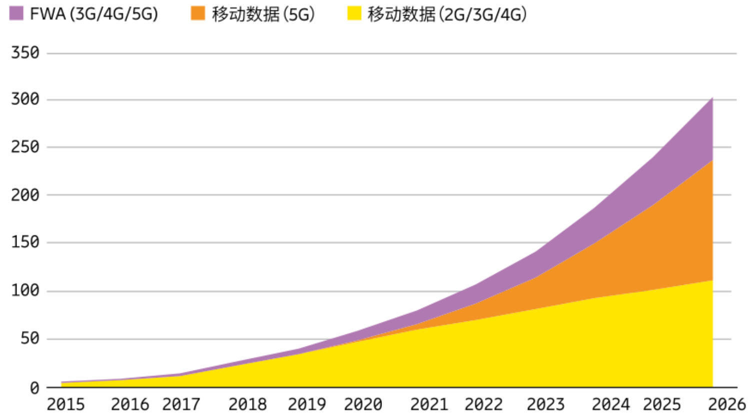
Fig. 1. Illustration of the cell free massive MIMO downlink systems.

Cell free massive MIMO

- Embrace the user-centric idea
- Eliminate the concept of cell boundaries
- Coverage enhancement
- Increased flexibility



Percentage of power consumed by different components



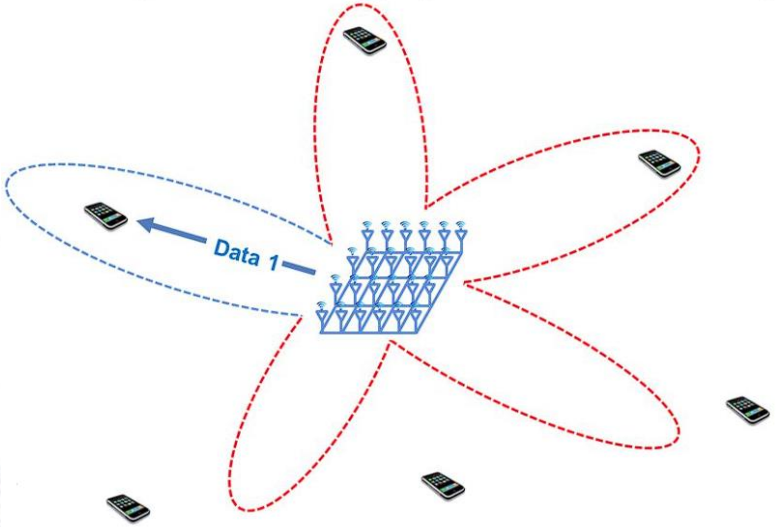
Growing demand for mobile traffic

Challenging issues about energy consumption and environmental pollution

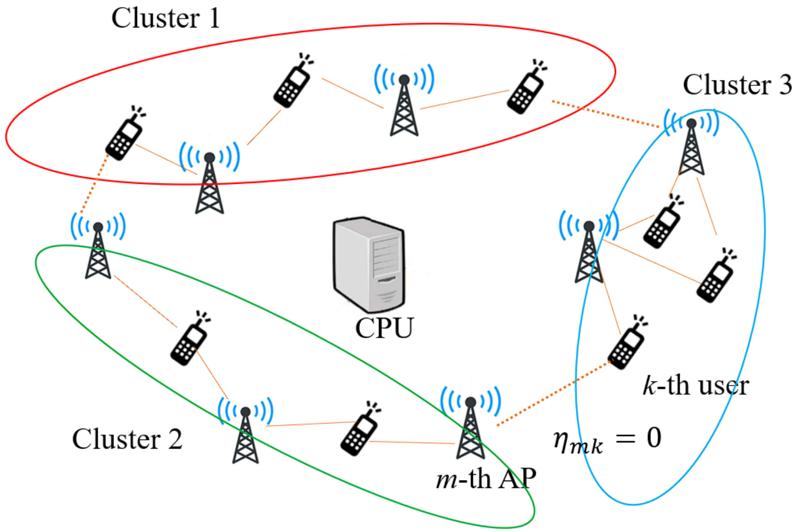
Energy efficiency optimization problem

1. Background

Precoding	AP selection
➢ Conjugate beamforming ⇨ high interference	➢ Reduce extra energy consumption
➢ Zero forcing ⇨ complex matrix inversion	➢ Suitable for the practical implementation
➢ Normalized conjugate beamforming	➢ Avoid substantial pilot contamination



Conjugate beamforming: directional transmission of signals for users



Cell free massive MIMO systems with AP selection

2. System Model

Downlink energy efficiency (EE)

$$SINR_k(\{\eta_{mk}\}) = \frac{\rho_d \Gamma_N^2 \left(\sum_{m=1}^{M} \sqrt{\eta_{mk}\alpha_{mk}}\right)^2}{1 + \rho_d \sum_{k'=1}^{K}\sum_{m=1}^{M} \eta_{mk'}\beta_{mk} + (N-1-\Gamma_N^2)\rho_d \sum_{m=1}^{M}\eta_{mk}\alpha_{mk} + \rho_d \sum_{k' \neq k}^{K} \gamma_{kk'} |\psi_k^H \psi_{k'}|^2}$$

spectral efficiency

$$S_{ek}(\{\eta_{mk}\}) = \log_2\left(1 + SINR_k\left(\{\eta_{mk}\}\right)\right)$$

$$E_e(\{\eta_{mk}\}) = \frac{BS_e(\{\eta_{mk}\})}{P_{\text{total}}} = \frac{B\sum_{k=1}^{K} S_{ek}(\{\eta_{mk}\})}{P_{\text{total}}}$$

bandwidth

$$P_{\text{total}} = \rho_d N_0 \sum_{m=1}^{M} \frac{1}{\mu_m}\left(\sum_{k=1}^{K}\eta_{mk}\right) + P_{fix} + BS_e(\{\eta_{mk}\}) \sum_{m=1}^{M} P_{\text{bt},m}$$

power consumption

How much energy it takes to reliably transmit a certain amount of information.

- Each AP with multiple antennas
- Presence of pilot contamination
- Channel estimation errors

2. System Model

EE optimization problem → finding → Optimal power allocation coefficients $\{\eta_{mk}\}$

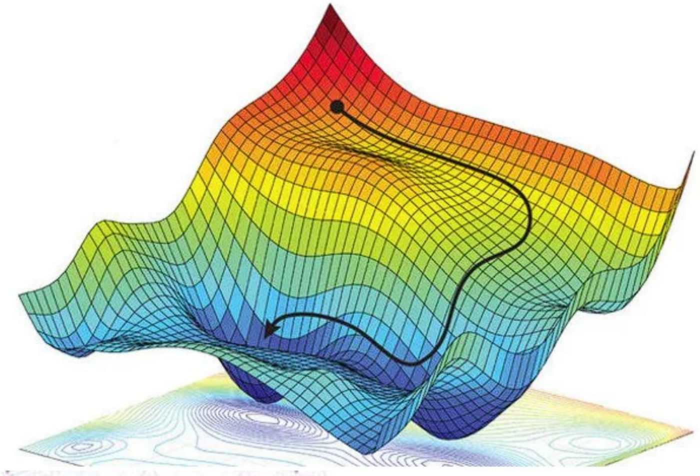
$\max_{\boldsymbol{\eta}} \quad E_e(\{\eta_{mk}\}),$ non-convex function containing complex logarithmic sums.

$\text{s.t.} \quad S_{ek}(\{\eta_{mk}\}) \geq S_{ok}, \forall k,$ ensure the reliable communication for all users.

$\rho_d \sum_{k=1}^{K} \eta_{mk} \leq \rho_d, \forall m,$ short-term power constraints for APs.

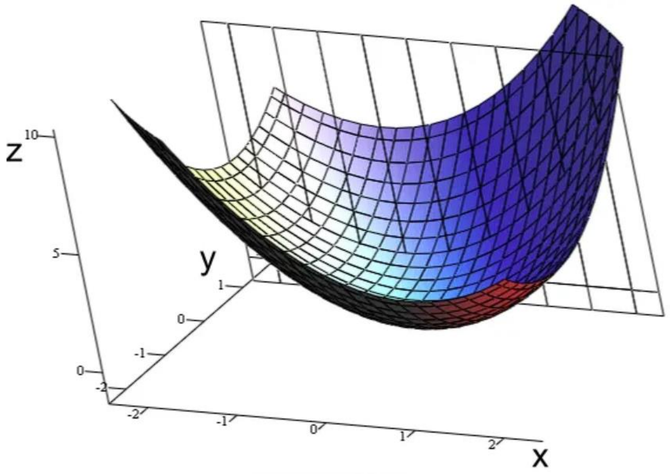
$\eta_{mk} \geq 0, \forall m, \forall k.$ guarantee non-negative power.

Non-convex optimization



non-convex optimization

How to transform it into a tractable form?



convex optimization

3. Power Allocation Scheme for NCB Precoding-based EE Optimization Problem

Main idea non-convex optimization problem → sequential convex approximation (SCA)

(1) Partial approximation of the objective function

$$SINR_k(\{\eta_{mk}\}) = \frac{\rho_d \Gamma_N^2 \left(\sum_{m=1}^{M} \sqrt{\eta_{mk}\alpha_{mk}}\right)^2}{1 + \rho_d \sum_{k'=1}^{K} \sum_{m=1}^{M} \eta_{mk'}\beta_{mk} + (N-1-\Gamma_N^2)\rho_d \sum_{m=1}^{M} \eta_{mk}\alpha_{mk} + \rho_d \sum_{k'\neq k}^{K} \gamma_{kk'} |\psi_k^H \psi_{k'}|^2}$$

user interference caused by the pilot contamination

$$\gamma_{kk'} \triangleq (N-1)\sum_{m=1}^{M} \eta_{mk'}\alpha_{mk'} \frac{\beta_{mk}^2}{\beta_{mk'}^2} + \Gamma_N^2 \sum_{m=1}^{M} \sum_{n\neq m}^{M} \sqrt{\eta_{mk'}\eta_{nk'}\alpha_{mk'}\alpha_{nk'}} \frac{\beta_{mk}\beta_{nk}}{\beta_{mk'}\beta_{nk'}}$$

$$\gamma_{kk'} \approx (N-1)\sum_{m=1}^{M} \eta_{mk'}\alpha_{mk'} \frac{\beta_{mk}^2}{\beta_{mk'}^2} + \Gamma_N^2 \left(\sum_{m=1}^{M} \sqrt{\eta_{mk'}\alpha_{mk'}} \frac{\beta_{mk}}{\beta_{mk'}}\right)^2$$

Dual summation: complex and intractable.

First-order approximation:
- High approximate accuracy.
- The objective function achieves a more tractable form.

(2) Transforming optimization variables and functions

Power allocation coefficients $\{\eta_{mk}\}$ → Denote $\{c_{mk}\} = \{\sqrt{\eta_{mk}}\}$: promote the quadratic convex transformation

Original problem	Optimization problem after introducing auxiliary variable $\{t_k\}$
$\max_{\boldsymbol{\eta}} \frac{BS_e(\{\eta_{mk}\})}{\rho_d N_0 \sum_{m=1}^{M} \frac{1}{\mu_m}\left(\sum_{k=1}^{K}\eta_{mk}\right) + P_{fix}},$ s.t. $S_{ek}(\{\eta_{mk}\}) \geq S_{ok}, \forall k,$ $\rho_d \sum_{k=1}^{K} \eta_{mk} \leq \rho_d, \forall m,$ $\eta_{mk} \geq 0, \forall m, \forall k.$	$\max_{\mathbf{c},\mathbf{t}} \frac{B\sum_{k=1}^{K} t_k}{\ln 2},$ (Simpler objective function) s.t. $\frac{\ln(1+SINR_k)}{P_{abs}} \geq t_k, \forall k,$ (non-convex constraint) $S_{ek}(\{c_{mk}\}) \geq S_{ok}, \forall k,$ $\sum_{k=1}^{K} c_{mk}^2 \leq 1, \forall m,$ $c_{mk} \geq 0, \forall m, \forall k.$ (convex constraints)

Second-order cone (SOC) constraint:

$$(\boldsymbol{\alpha}_k^T \mathbf{c}_k)^2 \geq (2^{S_{ok}}-1)\left(\frac{1}{\rho_d \Gamma_N^2} + \frac{\sum_{k'=1}^{K}\|\boldsymbol{\beta}_k \mathbf{c}_{k'}\|_2^2}{\Gamma_N^2} + \frac{(N-1-\Gamma_N^2)}{\Gamma_N^2}\|\boldsymbol{\alpha}_k \cdot \mathbf{c}_k\|_2^2 + \sum_{k'\neq k}^{K}\left(\boldsymbol{\xi}_{kk'}^T \mathbf{c}_{k'}\right)^2 \zeta_{kk'} + \frac{(N-1)}{\Gamma_N^2}\sum_{k'\neq k}^{K}\|\boldsymbol{\xi}_{kk'} \cdot \mathbf{c}_{k'}\|_2^2 \, \zeta_{kk'}\right), \forall k.$$

(3) Approximate non-convex constraint

➢ Original form

$$\frac{\ln(1+SINR_k)}{P_{abs}} \geq t_k, \forall k,$$

$$SINR_k(\{c_{mk}\}) = \frac{\Gamma_N^2(\boldsymbol{\alpha}_k^T \mathbf{c}_k)^2}{\frac{1}{\rho_d} + \sum_{k'=1}^K \|\boldsymbol{\beta}_k \mathbf{c}_{k'}\|_2^2 + (N-1-\Gamma_N^2)\|\boldsymbol{\alpha}_k \cdot \mathbf{c}_k\|_2^2 + \sum_{k'\neq k}^K \left((N-1)\|\boldsymbol{\xi}_{kk'} \cdot \mathbf{c}_{k'}\|_2^2 + \Gamma_N^2 \left(\boldsymbol{\xi}_{kk'}^T \mathbf{c}_{k'}\right)^2\right)\zeta_{kk'}}.$$

$$P_{abs} \triangleq \rho_d N_0 \sum_{m=1}^M \frac{1}{\mu_m}\left(\sum_{k=1}^K c_{mk}^2\right) + P_{fix} \in \mathbb{R},$$

➢ Step 1

$$\frac{\ln(1+x)}{t} \geq a - \frac{b}{x} - d \cdot t, \quad \forall x > 0, t > 0.$$

$$\frac{\ln(1+SINR_k)}{P_{abs}} \geq a_k^n - d_k^n P_{abs} - \frac{b_k^n}{\rho_d \Gamma_N^2 (\boldsymbol{\alpha}_k{}^T \mathbf{c}_k)^2} - \frac{\sum_{k'=1}^K \|\boldsymbol{\beta}_k \mathbf{c}_{k'}\|_2^2 + (N-1-\Gamma_N^2)\|\boldsymbol{\alpha}_k \cdot \mathbf{c}_k\|_2^2}{\Gamma_N^2 (\boldsymbol{\alpha}_k{}^T \mathbf{c}_k)^2 (b_k^n)^{-1}} - \frac{\sum_{k'\neq k}^K \left((N-1)\|\boldsymbol{\xi}_{kk'} \cdot \mathbf{c}_{k'}\|_2^2 + \Gamma_N^2 \left(\boldsymbol{\xi}_{kk'}^T \mathbf{c}_{k'}\right)^2\right)\zeta_{kk'}}{\Gamma_N^2 (\boldsymbol{\alpha}_k{}^T \mathbf{c}_k)^2 (b_k^n)^{-1}}$$

✦ Separate fractions containing logarithmic and quadratic term
✦ The right-hand-side (RHS) is still a non-convex function

➢ Step 2

$$\frac{x^2}{t} \geq 2\frac{\hat{x}x}{\hat{t}} - \frac{\hat{x}^2}{\hat{t}^2}t, \quad \forall x > 0, \hat{x} > 0, t > 0, \hat{t} > 0$$

✦ The quadratic term become the first-order term.

✦ Transform denominator term with quadratic optimization variables.

➢ Step 3

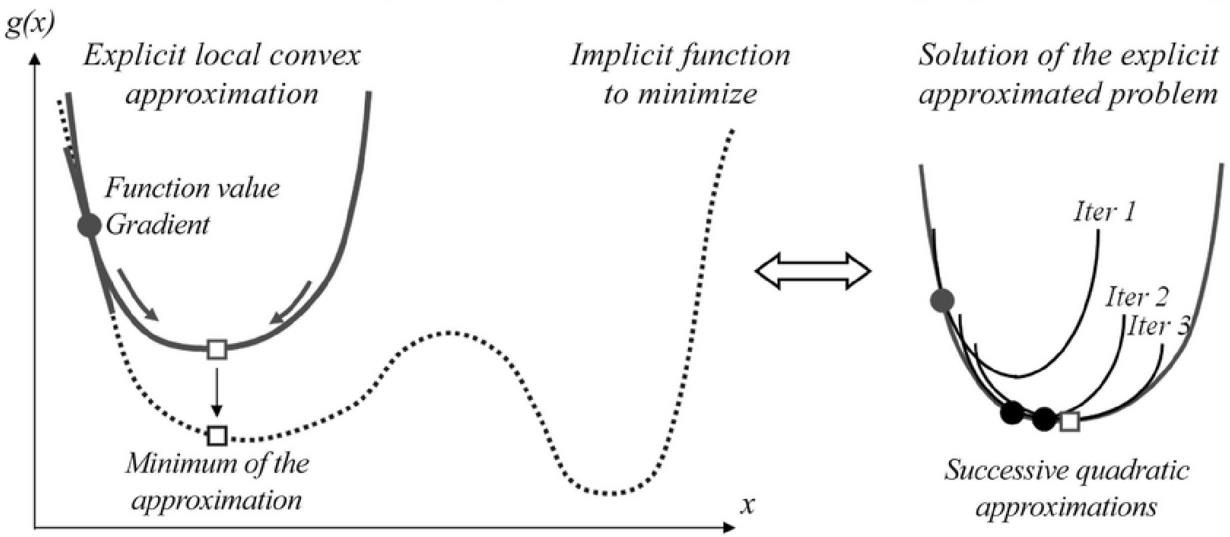
$$x^2 \geq 2\hat{x}x - \hat{x}^2, \quad \forall x \geq 0, \hat{x} \geq 0, 2x \geq \hat{x}$$

$$(\boldsymbol{\alpha}_k^T \mathbf{c}_k)^2 \geq 2(\boldsymbol{\alpha}_k^T \mathbf{c}_k^n)(\boldsymbol{\alpha}_k^T \mathbf{c}_k) - (\boldsymbol{\alpha}_k^T \mathbf{c}_k^n)^2, \forall k,$$
$$2c_{mk} \geq c_{mk}^n, \quad \forall m, \forall k.$$

✦ more computationally efficient formulation.

(4) Sequential convex approximation

Convex constraints after approximate transformation



- ➢ Iterative solve a series of accessible SOCP problems.
- ➢ The initial feasible solution is easy to obtain.

(5) Convergence analysis

n-th iteration optimal solution: $\{c_{mk}^{n}\}$

If $\{c_{mk}^{n}\}$= $\{c_{mk}^{*}\}$ "=" in convex inequalities

(n+1)-th iteration optimal solution: $\{c_{mk}^{*}\}$

feasible to original problem

Objective function consistently exhibits non-decreasing behavior

4. Further Improved By AP Selection

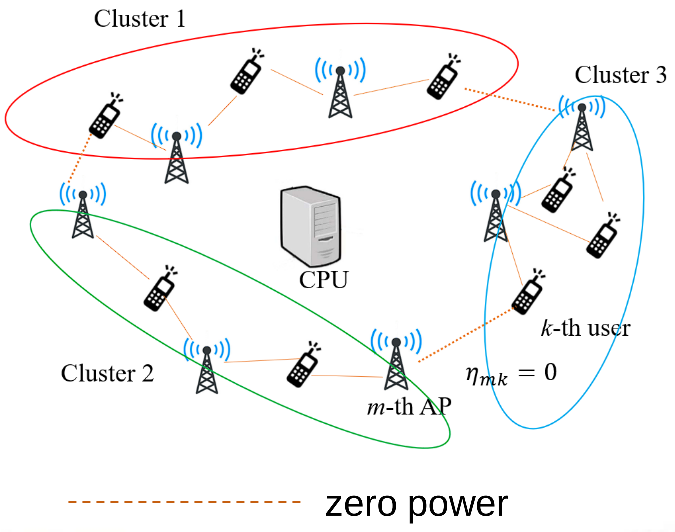
Motivation

- Shortage of pilot resources
- Additional backhaul overhead
- More severe interference between users with similar channels

- Initialization: set the number of clusters as $L = \left\lceil \frac{k}{\tau_u} \right\rceil$
- User clustering: clustering based on the similarity of $\{\beta_{mk}\}$
- Centroid position update: whether the clustering result is stable
- Modify cluster size: ensure the cluster use orthogonal pilots
- AP selection: services for clusters with the best channel quality

Algorithm 1 The Proposed Power Allocation Scheme For EE Optimization With NCB

Input: $S_{ok}, \rho_d, N, \{\alpha_{mk}\}, \{\beta_{mk}\}, N_I$
Output: power allocation coefficients $\{\eta_{mk}\} = \{c_{mk}^2\}$
Step 1: perform AP selection, go to Step 2; without AP selection, go to Step 4
Step 2: perform AP selection scheme based on the K-means++ to obtain the connectivity matrix $\mathbf{X}$
Step 3: if $\mathbf{X}_{mk} = 1$, let $\widehat{\alpha}_{mk} = \alpha_{mk}$; else $\widehat{\alpha}_{mk} = 0$, $\forall m, \forall k$. Replace $\{\alpha_{mk}\}$ with $\{\widehat{\alpha}_{mk}\}$ as Step 4 input, proceed to the next step
Step 4: obtain an initial feasible solution $\mathbf{c}^0$ by solving (25), set $n = 1$
Step 5: perform the n-th iteration: solving problem (24) by using SOCP solver, obtain optimal solution $\mathbf{c}^*$
Step 6: when $n = N_I$, terminate the algorithm; else go to Step 7
Step 7: update $\mathbf{c}^n = \mathbf{c}^*, n = n + 1$, go to Step 5



Pilot contamination:

- Same cluster: $\left|\psi_k^H \psi_{k'}\right| = 0$
- Different clusters: $\left|\psi_k^H \psi_{k'}\right| \neq 0$
  $\eta_{mk}\eta_{mk'} = 0 \rightarrow \gamma_{kk'} = 0$

Eliminate the interference caused by pilot contamination

5. Simulation Results

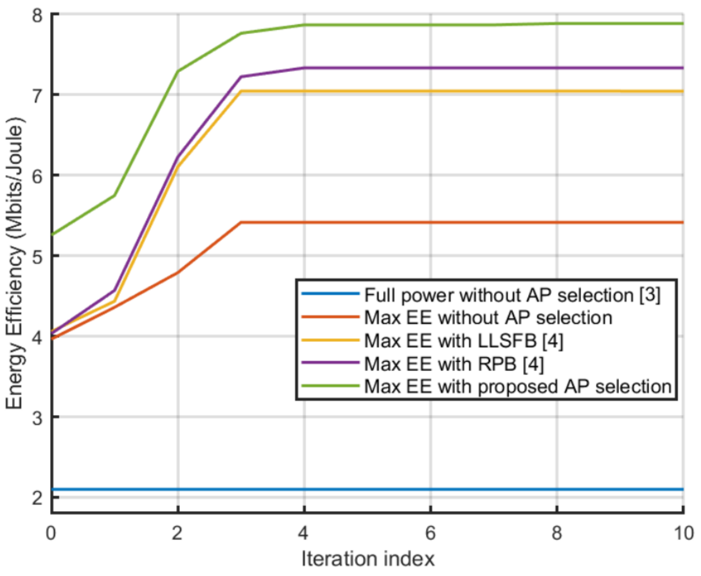


Fig. 2. Illustration of the energy efficiency versus the number of iterations $(M = 100, N = 1, K = 20, \tau_u = 5, D = 1)$.

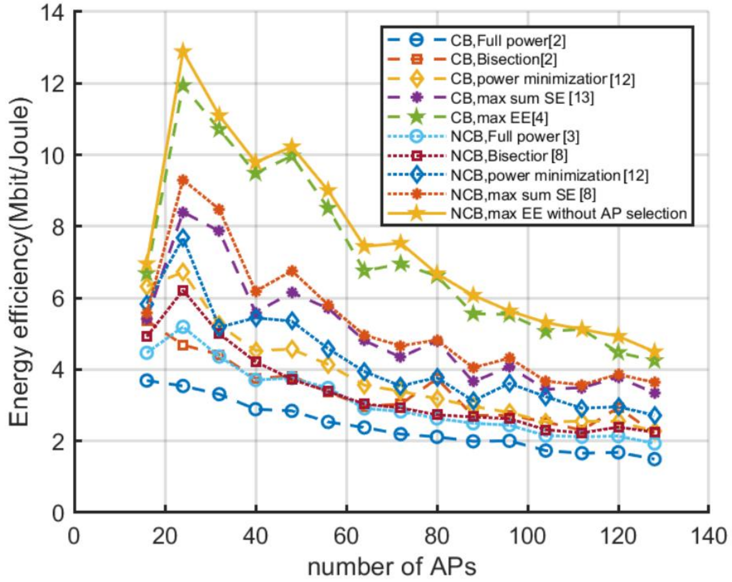


Fig. 3. Illustration of downlink energy efficiency versus the number of APs, comparison of proposed scheme with other power allocation schemes $(N = 2, K = 16, \tau_u = 16, D = 1)$.

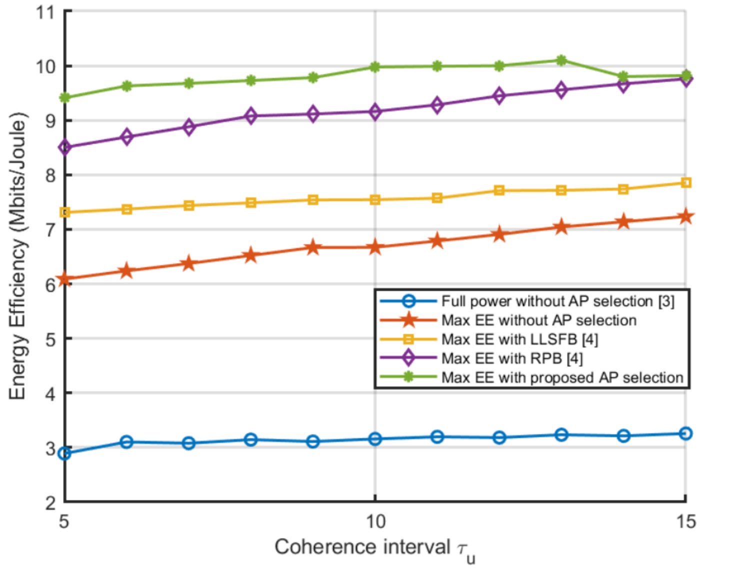


Fig. 4. Illustration of the downlink energy efficiency versus the coherence interval $(M = 100, N = 1, K = 40, D = 1)$.

Converges with only a few iterations.

Significant improvement in energy efficiency compared to other power allocation schemes.

Further improved by AP selection:

- Reduce the backhaul power consumption
- Eliminate the interference caused by pilot contamination.

THANK FOR YOUR WATCHING

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