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Analog-only beamforming for near-field multiuser MIMO communications

Key words: Beam focusing; Beamforming; Majorization–minimization; Multiuser communications; Near field

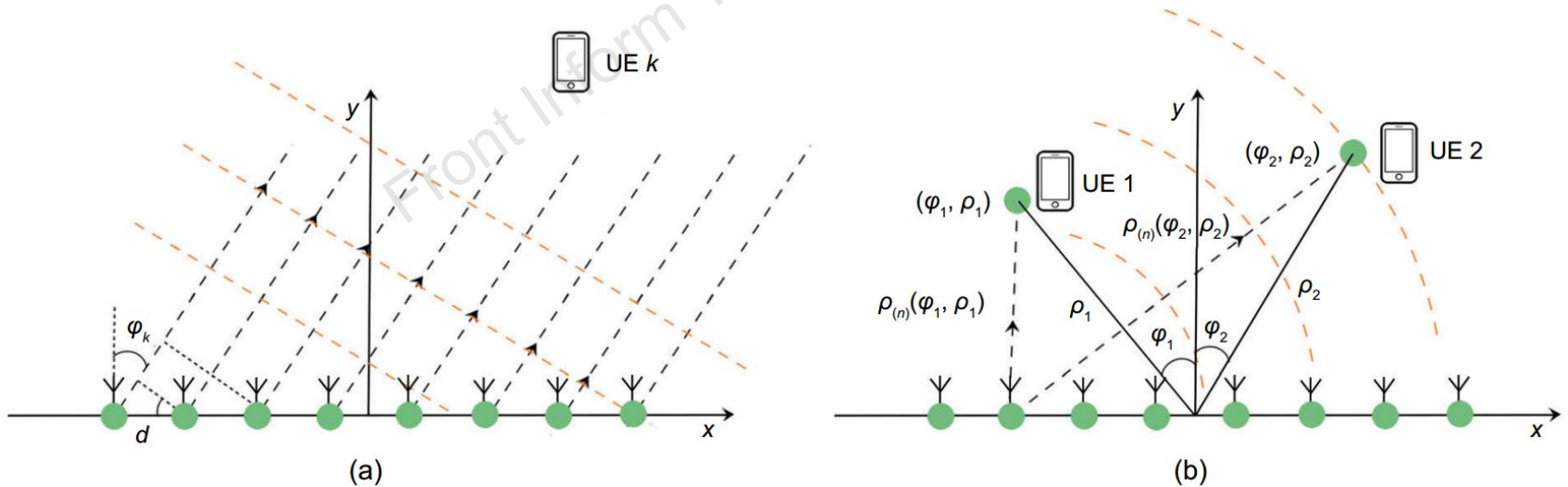
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Motivation

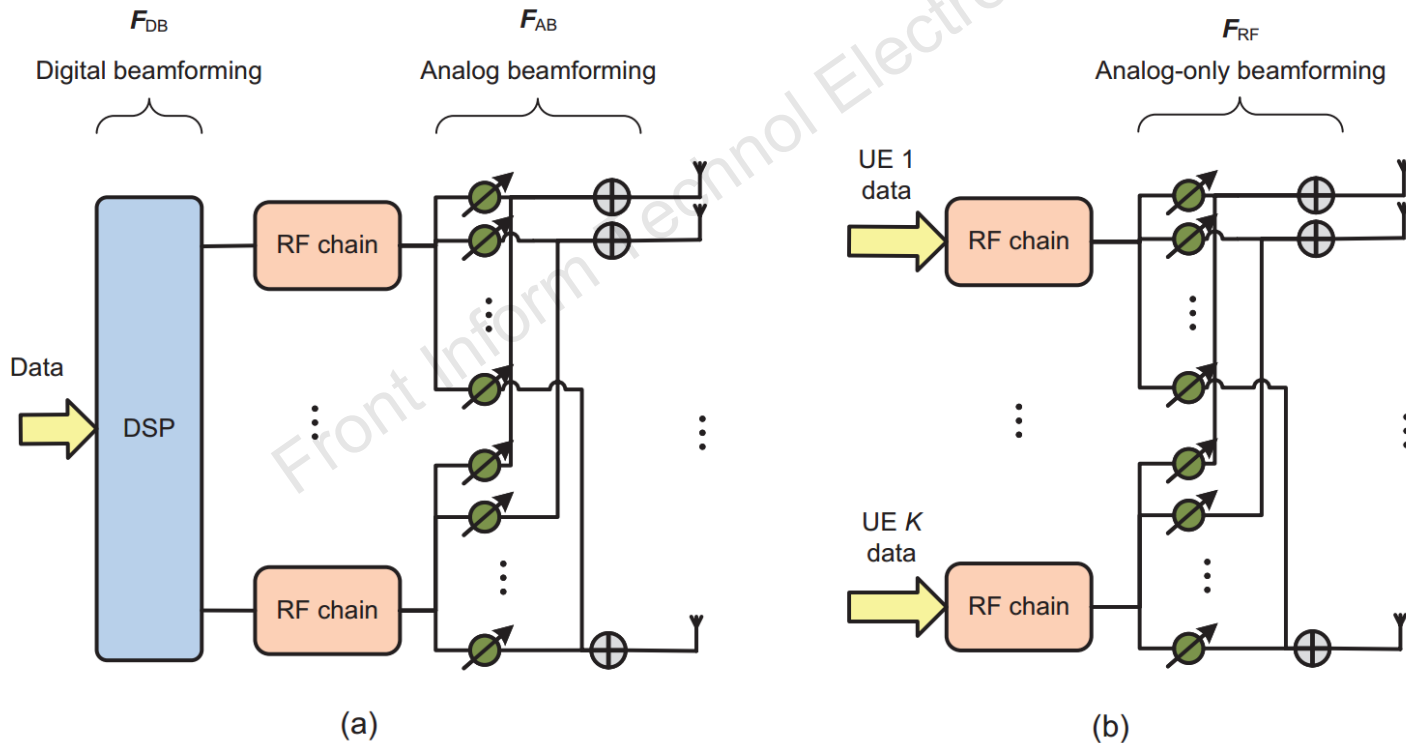
- Different from far field, wireless propagation in the near field is precisely modeled as spherical waves instead of plane waves. Thus, the near-field beam can be focused on a specific location, which is different from the far-field beam aligned to a certain angle regardless of distance. Therefore, conventional far-field multiuser interference suppression methods may not be suitable for near-field multiuser communications.



Channel models in the far field (a) and the near field (b)

Motivation

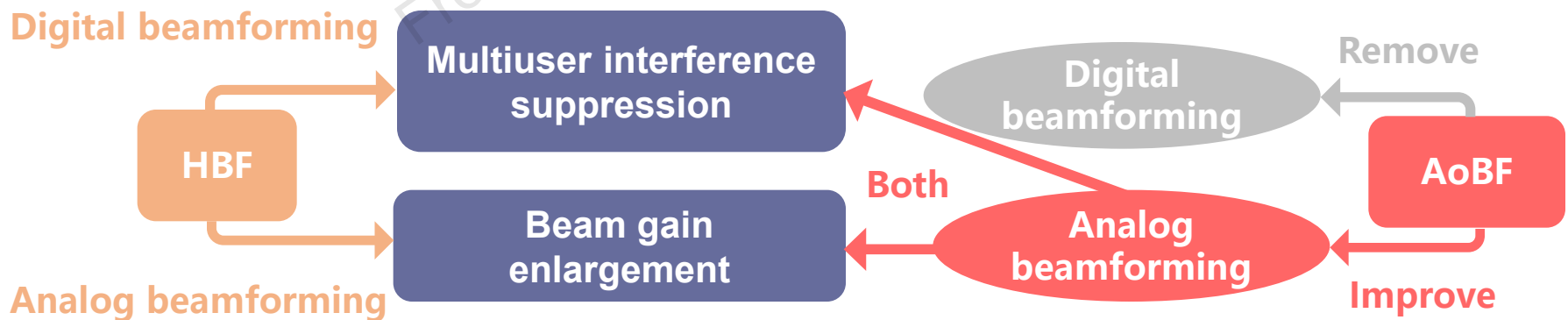
□ To simplify the system reconfiguration and eliminate the pilot overhead required by effective channel estimation, we consider using the analog-only beamforming (AoBF) architecture to replace the hybrid beamforming (HBF) architecture.



Beamforming architecture comparison: (a) HBF architecture; (b) AoBF architecture

Motivation

- ❑ The conventional HBF is implemented by the combination of analog beamforming and digital beamforming. Typically, analog beamforming concentrates on the beam gain enlargement via beam focusing. Digital beamforming is designed mainly for multiuser interference suppression.
- ❑ AoBF is committed to performing both beam gain enlargement and multiuser interference suppression relying only on analog beamforming.



Main idea

□ In this study, AoBF is designed to maximize the sum rate. Then, it is transformed into a problem maximizing the power transmitted to the target user equipment (UE) and meanwhile minimizing the power leaked to the other UEs. To solve this problem, we propose two AoBF schemes:

- The AoBF scheme based on perfect channel state information (CSI) is proposed to show the feasibility of replacing HBF with AoBF in the near field, with the focus on beamforming performance and regardless of CSI acquisition.
- The AoBF scheme based on imperfect CSI is proposed to meet the practical requirement, where a heuristic method is designed to approximate the channel vector by generating auxiliary points within the best-codeword area.

Method

- ① Maximizing the sum rate is equivalent to maximizing the signal-to-interference-plus-noise ratio (SINR) of each UE.
- ② As beamforming for all UEs is coupled in SINR, the SINR is replaced by the signal-to-leakage-and-noise ratio (SLNR).
- ③ Maximize the power focused on the target UE and meanwhile minimize the power leaked to the other UEs.

Maximize the sum rate

$$\begin{aligned} & \max_{\mathbf{F}} \sum_{k=1}^K R_k \\ & \text{s.t. } \|\mathbf{F}\|_F = K, \\ & R_k \triangleq \log_2(1 + \text{SINR}_k) \end{aligned}$$

①

Maximize the SINR

$$\begin{aligned} & \max_{\mathbf{F}} \text{SINR}_k \\ & \text{s.t. } \|\mathbf{F}\|_F = K. \\ & \text{SINR}_k \triangleq \frac{\frac{P}{K} |h_k^H [\mathbf{F}]_{:,k}|^2}{\frac{P}{K} \sum_{i \neq k} |h_k^H [\mathbf{F}]_{:,i}|^2 + \sigma^2}. \end{aligned}$$

②

Maximize the SLNR

$$\begin{aligned} & \max_{[\mathbf{F}_{\text{RF}}]_{:,k}} \text{SLNR}_k \\ & \text{s.t. } |[\mathbf{F}_{\text{RF}}]_{n,k}| = \frac{1}{\sqrt{N_{\text{BS}}}}. \\ & \text{SLNR}_k \triangleq \frac{\frac{P}{K} |h_k^H [\mathbf{F}_{\text{RF}}]_{:,k}|^2}{\frac{P}{K} \sum_{i \neq k} |h_i^H [\mathbf{F}_{\text{RF}}]_{:,k}|^2 + \sigma^2}. \end{aligned}$$

③

Maximize the power focused on the target UE
&
Minimize the power leaked to the other UEs

$$\min_{[\mathbf{F}_{\text{RF}}]_{:,k}} \left(-|h_k^H [\mathbf{F}_{\text{RF}}]_{:,k}|^2 + \omega \sum_{i \neq k} |h_i^H [\mathbf{F}_{\text{RF}}]_{:,k}|^2 \right).$$

Method

- To solve this non-convex problem, we use beam focusing and beam nulling based on the majorization–minimization (MM) method, which is an iterative algorithm with each iteration consisting of a majorization stage and a minimization stage.
- In the majorization stage, the original non-convex objective function is transformed into a surrogate function that is easy to optimize at the feasible point.
 - In the minimization stage, the surrogate function is minimized to update the feasible point.

Non-convex problem

$$\min_{[\mathbf{F}_{\text{RF}}]_{:,k}} \left(-\left| \mathbf{h}_k^H [\mathbf{F}_{\text{RF}}]_{:,k} \right|^2 + \omega \sum_{i \neq k}^K \left| \mathbf{h}_i^H [\mathbf{F}_{\text{RF}}]_{:,k} \right|^2 \right).$$

Closed-form solution

$$[\mathbf{F}_{\text{RF}}]_{n,k}^{(t+1)} = e^{j\angle \left(\left(\left(\Pi_1^{(t)} - \omega \Pi_2^{(t)} \right) [\mathbf{F}_{\text{RF}}]_{:,k}^{(t)} \right)_n \right)}.$$

Convex problem

$$\max_{[\mathbf{F}_{\text{RF}}]_{:,k}} \left\| \left[\mathbf{F}_{\text{RF}} \right]_{:,k}^H + \left(\Pi_1^{(t)} - \omega \Pi_2^{(t)} \right) \left[\mathbf{F}_{\text{RF}} \right]_{:,k}^{(t)} \right\|_{\text{F}}^2$$

$$\Pi_1^{(t)} \triangleq \mathbf{h}_k \mathbf{h}_k^H,$$

$$\Pi_2^{(t)} \triangleq \sum_{i \neq k}^K \left(\mathbf{h}_i \mathbf{h}_i^H - \mu \mathbf{I}_{N_{\text{BS}}} \right),$$

Method

- In practice, the perfect CSI is unknown, and the estimation of high-dimensional CSI is challenging. Normally, to address this problem, beam sweeping is performed to obtain low-dimensional imperfect CSI. Since the best code word selected by near-field beam sweeping corresponds to an area rather than an accurate location, we propose a heuristic method to approximate the unknown channel via auxiliary points within this area.

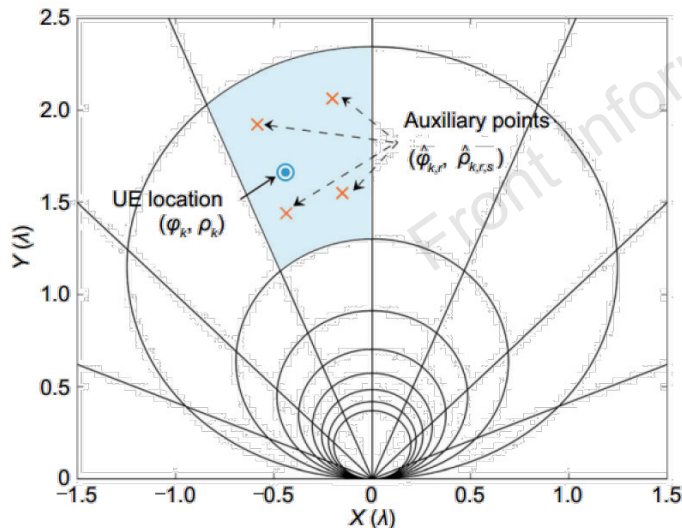


Illustration of beam sweeping code words and auxiliary points

Codebook

$$\begin{cases} \mathbf{v}_{p,q} \triangleq \mathbf{u}(\bar{\varphi}_p, \bar{\rho}_{p,q}), \\ \bar{\varphi}_p \triangleq \arcsin\left(\frac{2p-1}{N_{\text{BS}}}-1\right), \quad p = 1, 2, \dots, N_{\text{BS}}, \\ \bar{\rho}_{p,q} \triangleq \frac{N_{\text{BS}}^2 d^2}{2q\beta_{\Delta}^2 \lambda} \{1 - \sin^2 \varphi_p\}, \quad q = 1, 2, \dots, N_{\text{DIS}}, \end{cases}$$

Auxiliary points

$$\begin{cases} \hat{\varphi}_{k,r} \triangleq \arcsin\left(\frac{2\hat{\rho}_{k,r}-1}{RN_{\text{BS}}}-1\right), \\ \hat{\rho}_{k,r} \triangleq R(\tilde{\rho}_k - 1) + r, \\ r = 1, 2, \dots, R. \end{cases}$$

$$\begin{cases} \hat{\rho}_{k,r,s} \triangleq \frac{N_{\text{BS}}^2 d^2}{2\hat{q}_{k,s}\beta_{\Delta}^2 \lambda} (1 - \sin^2 \hat{\varphi}_{k,r}), \\ \hat{q}_{k,s} \triangleq \frac{4S}{2S\left(\frac{1}{\hat{q}_k} + \frac{1}{\hat{q}_{k+1}}\right) + \left(\frac{1}{\hat{q}_k-1} - \frac{1}{\hat{q}_{k+1}}\right)(2s-1)}, \\ s = 1, 2, \dots, S. \end{cases}$$

Method

- The steering vectors corresponding to the auxiliary points within the area are used to approximate the channel vector.

Maximize the SLNR

$$\begin{aligned} & \max_{[\mathbf{F}_{\text{RF}}]_{:,k}} \text{SLNR}_k \\ \text{s.t. } & |[\mathbf{F}_{\text{RF}}]_{n,k}| = \frac{1}{\sqrt{N_{\text{BS}}}}. \\ \text{SLNR}_k & \triangleq \frac{\frac{P}{K} |\mathbf{h}_k^H [\mathbf{F}_{\text{RF}}]_{:,k}|^2}{\frac{P}{K} \sum_{i \neq k} |\mathbf{h}_i^H [\mathbf{F}_{\text{RF}}]_{:,k}|^2 + \sigma^2}. \end{aligned}$$



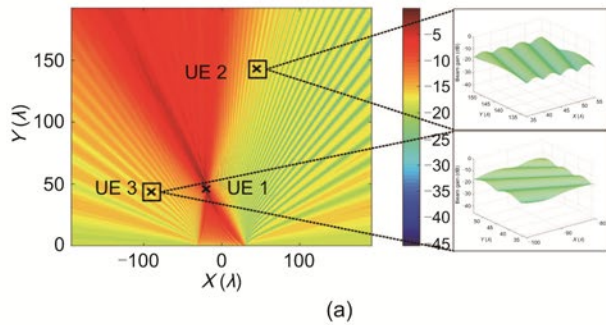
Maximize the approximated SLNR

$$\begin{aligned} & \max_{[\mathbf{F}_{\text{RF}}]_{:,k}} \frac{\frac{1}{RS} \sum_{r=1}^R \sum_{s=1}^S |\mathbf{u}^H(\hat{\varphi}_{k,r}, \hat{\rho}_{k,r,s}) [\mathbf{F}_{\text{RF}}]_{:,k}|^2}{\frac{1}{RS} \sum_{i \neq k} \sum_{r=1}^R \sum_{s=1}^S |\mathbf{u}^H(\hat{\varphi}_{i,r}, \hat{\rho}_{i,r,s}) [\mathbf{F}_{\text{RF}}]_{:,k}|^2 + \sigma^2}. \\ \mathbf{u}(\varphi_k, \rho_k) & \triangleq \frac{1}{\sqrt{N_{\text{BS}}}} \left[e^{\frac{-j2\pi\rho(1)(\varphi_k, \rho_k)}{\lambda}}, \dots, e^{\frac{-j2\pi\rho(N_{\text{BS}})(\varphi_k, \rho_k)}{\lambda}} \right]^T. \end{aligned}$$

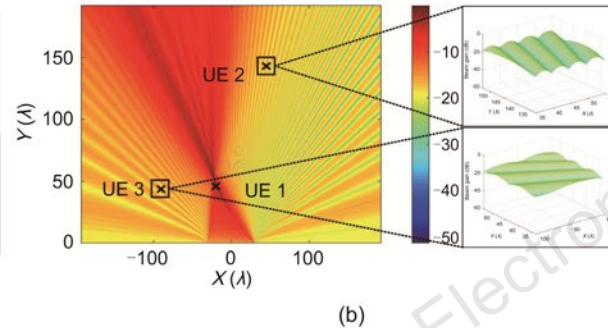
- The closed-form solution in the t^{th} iteration of MM optimization can be denoted as

$$\begin{aligned} [\mathbf{F}_{\text{RF}}]_{n,k}^{(t+1)} &= e^{j\angle\left(\left[\left(\Omega_i^{(t)} - \omega\Omega_2^{(t)}\right)[\mathbf{F}_{\text{RF}}]_{:,k}^{(t)}\right]_n\right)}, \\ \Omega_1^{(t)} &\triangleq \sum_{r=1}^R \sum_{s=1}^S \mathbf{u}(\hat{\varphi}_{k,r}, \hat{\rho}_{k,r,s}) \mathbf{u}^H(\hat{\varphi}_{k,r}, \hat{\rho}_{k,r,s}), \\ \Omega_2^{(t)} &\triangleq \sum_{i \neq k} \sum_{r=1}^R \sum_{s=1}^S \left\{ \mathbf{u}(\hat{\varphi}_{i,r}, \hat{\rho}_{i,r,s}) \mathbf{u}^H(\hat{\varphi}_{i,r}, \hat{\rho}_{i,r,s}) - \frac{1}{N_{\text{BS}}} \mathbf{I}_{N_{\text{BS}}} \right\}. \end{aligned}$$

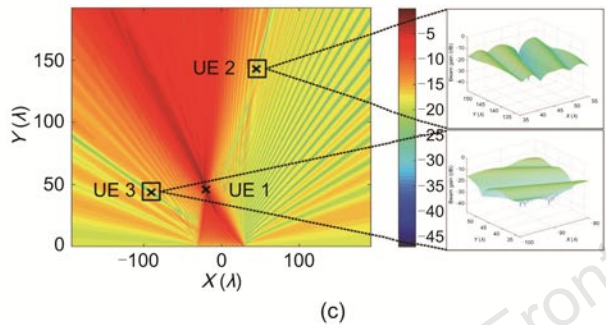
Major results



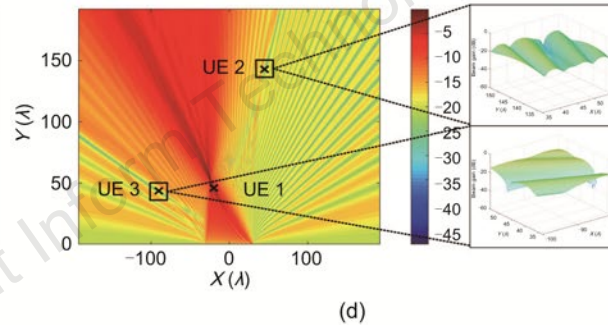
(a)



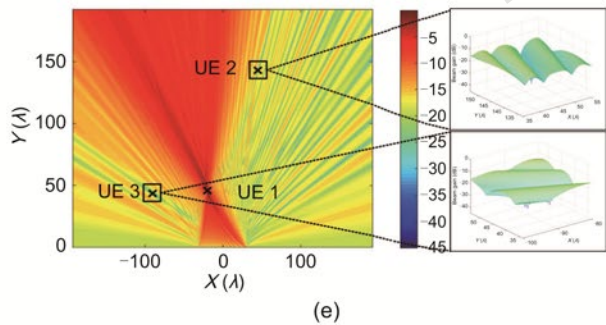
(b)



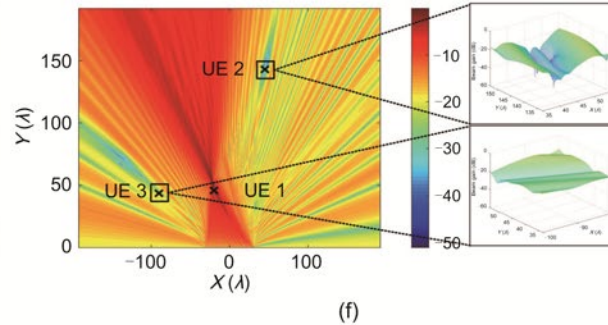
(c)



(d)



(e)

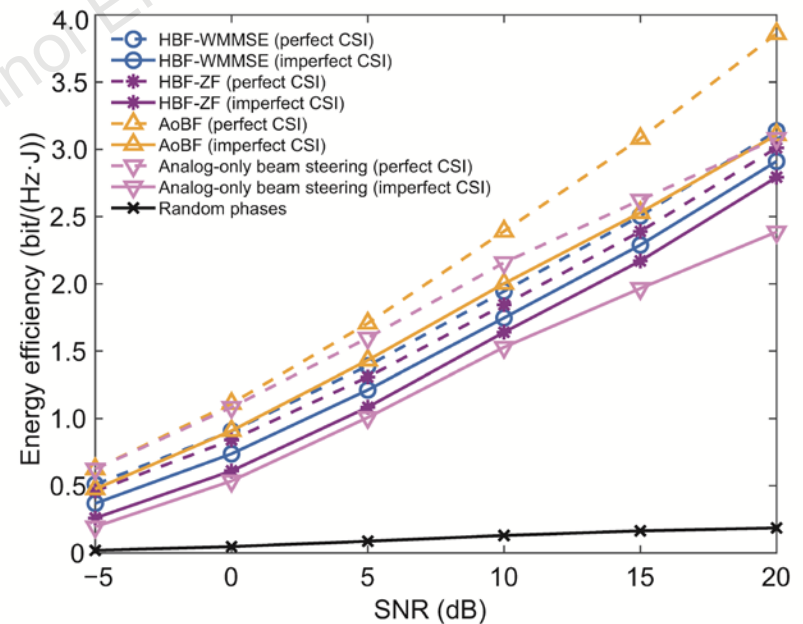
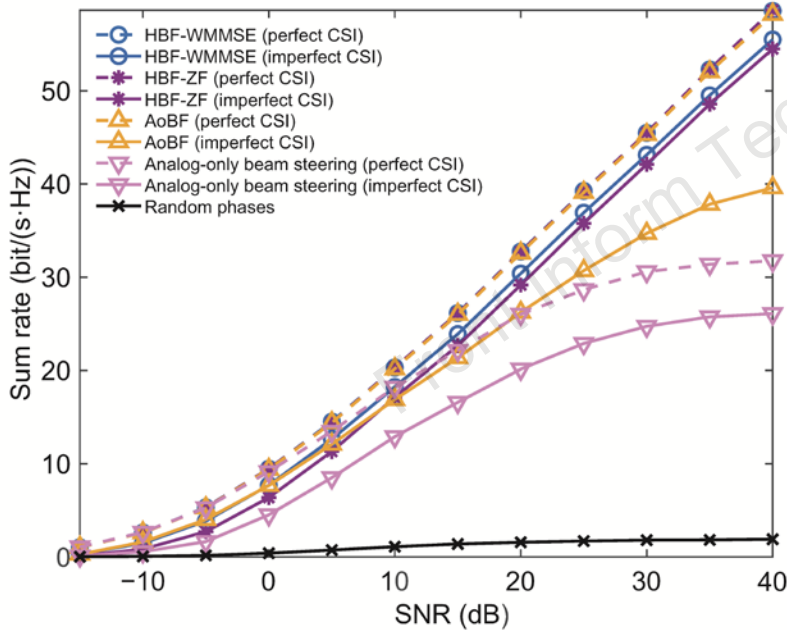


(f)

Beam pattern comparison:
(a) beam pattern generated by analog-only beam steering based on perfect CSI;
(b) beam pattern generated by analog-only beam steering based on imperfect CSI;
(c) beam pattern generated by HBF with WMMSE based on perfect CSI;
(d) beam pattern generated by HBF with WMMSE based on imperfect CSI;
(e) beam pattern generated by AoBF based on perfect CSI;
(f) beam pattern generated by AoBF based on imperfect CSI

Major results

- Simulation results demonstrate that the proposed two AoBF schemes can approach HBF schemes in terms of the sum rate and outperform HBF schemes in terms of energy efficiency.



Conclusions

In this study, we have proposed two AoBF schemes for multiuser near-field communications based on perfect CSI and imperfect CSI, separately. The proposed AoBF schemes can approach the performance of HBF with a simplified system configuration and higher energy efficiency. Future studies will focus on the AoBF design based on physically consistent modeling.



Ying WANG received the BS degree in electronic science and technology and the ME degree in circuits and systems from Southeast University, China, in 2017 and 2021, respectively. She is currently pursuing the PhD degree in information and communication engineering with the School of Information Science and Engineering, Southeast University. Her research interests include mmWave communications, beam training and beamforming, near-field communications, and machine learning.



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