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Beamforming and fronthaul compression design for intelligent reflecting surface aided cloud radio access networks

Key words: Cloud radio access network (C-RAN); Intelligent
reflecting surface (IRS); Transmit beamforming; Fronthaul
compression

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Motivation

1. With the development of AI, IoT, mobile Internet, and industrial Internet, it is necessary to build intelligence-endogenous and primitive-concise wireless networks, which integrate communication, computing, caching, and control (the 4Cs) with AI.
2. C-RAN is one of the potential candidate network structures. However, to further enhance the capacity and coverage, more radio remote heads (RRHs) as well as high-fidelity and low-latency fronthaul links are required, which leads to high implementation cost.
3. IRS is basically a passive device. It can generate the desired reflection beams and create favorable propagation conditions. Hence, it is an energy-efficient and cost-effective way to enhance C-RAN.

Main idea

1. For the IRS-assisted C-RAN uplink transmission, wherein multiple IRSs are deployed between multi-antenna users and RRHs, we investigate the joint design of user transmit beamforming, IRS passive beamforming, and fronthaul compression under P2P compression and Wyner-Ziv compression schemes, with the goal of maximizing the uplink sum rate.
2. The design problem is non-convex, wherein the transmit beamformers, passive beamformers, and fronthaul compression noise covariance matrices are coupled. By exploiting the Arimoto-Blahut algorithm and SDR, we propose two iterative algorithms based on successive convex approximation (SCA) for the cases of P2P compression and Wyner-Ziv coding, respectively.

System model

We consider the uplink transmission of a C-RAN, where K multi-antenna users communicate with the BBU pool through L RRHs, as depicted in Fig. 1. Each user and each RRH are equipped with N_U and N_R antennas, respectively. M IRSs are deployed to aid the communication between the users and RRHs, each of which has N_I reflection elements.

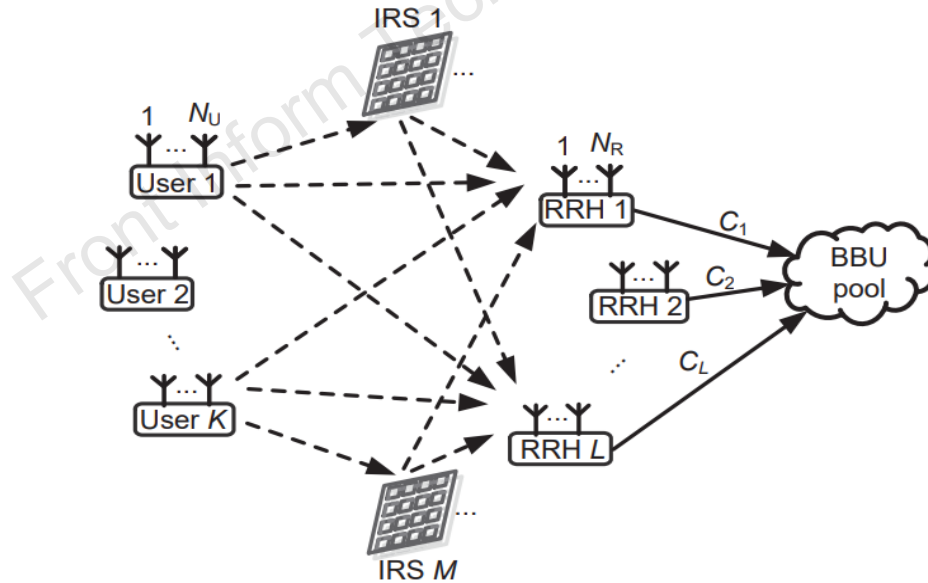


Fig. 1 System model

Problem formulation

We investigate the joint optimization of user transmit beamformers, IRS passive beamformers, and compression noise covariance matrices to maximize the uplink sum rate subject to fronthaul capacity constraints under P2P compression and Wyner-Ziv coding.

For P2P compression:

$$\begin{aligned} & \max_{\mathbf{F}_k, \boldsymbol{\Theta}, \boldsymbol{\Omega}_l} \left(\log_2 |\mathbf{V}_{\mathcal{L}} \mathbf{F}_{\mathcal{K}} \mathbf{F}_{\mathcal{K}}^H \mathbf{V}_{\mathcal{L}}^H + \sigma^2 \mathbf{I} + \boldsymbol{\Omega}_{\mathcal{L}}| \right. \\ & \quad \left. - \log_2 |\sigma^2 \mathbf{I} + \boldsymbol{\Omega}_{\mathcal{L}}| \right) \\ \text{s.t. } & \begin{cases} \log_2 |\mathbf{V}_l \mathbf{F}_{\mathcal{K}} \mathbf{F}_{\mathcal{K}}^H \mathbf{V}_l^H + \sigma^2 \mathbf{I} + \boldsymbol{\Omega}_l| - \log_2 |\boldsymbol{\Omega}_l| \leq C_l, \\ \text{tr}(\mathbf{F}_k \mathbf{F}_k^H) \leq P_k, \forall k \in \mathcal{K}, \\ \boldsymbol{\Omega}_l \succeq 0, \forall l \in \mathcal{L}, \\ |\theta_{m,n}| = 1, \forall m, n. \end{cases} \end{aligned}$$

Problem formulation (Cont'd)

For Wyner-Ziv coding compression:

$$\max_{F_k, \Theta, \Omega_{\mathcal{L}}} \left(\log_2 |V_{\mathcal{L}} F_{\mathcal{K}} F_{\mathcal{K}}^H V_{\mathcal{L}}^H + \sigma^2 I + \Omega_{\mathcal{L}}| \right. \\ \left. - \log_2 |\sigma^2 I + \Omega_{\mathcal{L}}| \right)$$

$$\text{s.t.} \begin{cases} \log_2 |V_{\mathcal{L}} F_{\mathcal{K}} F_{\mathcal{K}}^H V_{\mathcal{L}}^H + \sigma^2 I + \Omega_{\mathcal{L}}| \\ \quad + \log_2 |V_{\mathcal{S}} F_{\mathcal{K}} F_{\mathcal{K}}^H V_{\mathcal{S}}^H + \sigma^2 I + \Omega_{\mathcal{S}}| \\ \quad - \log_2 |\Omega_{\mathcal{S}}| \leq C_{\mathcal{S}}, \forall \mathcal{S}, \\ \text{tr}(F_k F_k^H) \leq P_k, \forall k \in \mathcal{K}, \\ |\theta_{m,n}| = 1, \forall m, n, \\ \Omega_l \succeq 0, \forall l \in \mathcal{L}. \end{cases}$$

Method

Due to the non-convexity of the objective function, the fronthaul constraints, and the last constraint in the following problem, by exploiting the Arimoto-Blahut algorithm and SDR, we propose an SCA approach to make problems tractable.

For P2P compression, the problem is transformed into

$$\begin{aligned} & \max_{\mathbf{E}_l, \mathbf{W}, \boldsymbol{\Sigma}, \mathbf{F}_k, \boldsymbol{\Theta}, \boldsymbol{\Omega}_l} \mathbb{E} \left[\log_2 \left(\frac{\mathcal{CN}(\mathbf{W} \hat{\mathbf{y}}_{\mathcal{L}}, \boldsymbol{\Sigma})}{\mathcal{CN}(\mathbf{0}, \mathbf{I})} \right) \right] \\ \text{s.t. } & \begin{cases} \log_2 |\mathbf{E}_l| + \text{tr}(\mathbf{E}_l^{-1} \boldsymbol{\Gamma}_l) - N_{\text{R}} - \log_2 |\boldsymbol{\Omega}_l| \leq C_l, \\ \text{tr}(\mathbf{F}_k \mathbf{F}_k^{\text{H}}) \leq P_k, \forall k \in \mathcal{K}, \\ \boldsymbol{\Omega}_l \succeq \mathbf{0}, \forall l \in \mathcal{L}, \\ |\theta_{m,n}| = 1, \forall m, n. \end{cases} \end{aligned}$$

Method (Cont'd)

For the Wyner-Ziv coding compression:

$$\begin{aligned}
 & \max_{\substack{\mathbf{W}, \boldsymbol{\Sigma}, \mathbf{E}_{\mathcal{L}}, \mathbf{F}_k, \\ \boldsymbol{\Theta}, \boldsymbol{\Omega}_{\mathcal{L}}, \mathbf{W}_{\bar{\mathcal{S}}}, \boldsymbol{\Sigma}_{\bar{\mathcal{S}}}}} \mathbb{E} \left[\log_2 \left(\frac{\mathcal{CN}(\mathbf{W}\hat{\mathbf{y}}_{\mathcal{L}}, \boldsymbol{\Sigma})}{\mathcal{CN}(\mathbf{0}, \mathbf{I})} \right) \right] \\
 & \log_2 |\mathbf{E}_{\mathcal{L}}| + \text{tr}(\mathbf{E}_{\mathcal{L}}^{-1} \mathbf{F}_{\mathcal{L}}) - \mathbb{E} \left[\log_2 \left(\frac{\mathcal{CN}(\mathbf{W}_{\bar{\mathcal{S}}} \hat{\mathbf{y}}_{\bar{\mathcal{S}}}, \boldsymbol{\Sigma}_{\bar{\mathcal{S}}})}{\mathcal{CN}(\mathbf{0}, \mathbf{I})} \right) \right] \\
 & - \log_2 |\boldsymbol{\Omega}_{\mathcal{S}}| - \log_2 |\sigma^2 \mathbf{I} + \boldsymbol{\Omega}_{\bar{\mathcal{S}}}| - LN_{\text{R}} \leq C_{\mathcal{S}}, \forall \mathcal{S}, \\
 & \text{tr}(\mathbf{F}_k \mathbf{F}_k^{\text{H}}) \leq P_k, \forall k \in \mathcal{K}, \\
 & \boldsymbol{\Omega}_l \succeq \mathbf{0}, \forall l \in \mathcal{L}, \\
 & |\theta_{m,n}| = 1, \forall m, n.
 \end{aligned}$$

Both problems can be solved by alternating optimization, SDR, and the convex optimization tool.

Major results

Average sum rate versus the number of iterations and the number of IRSs

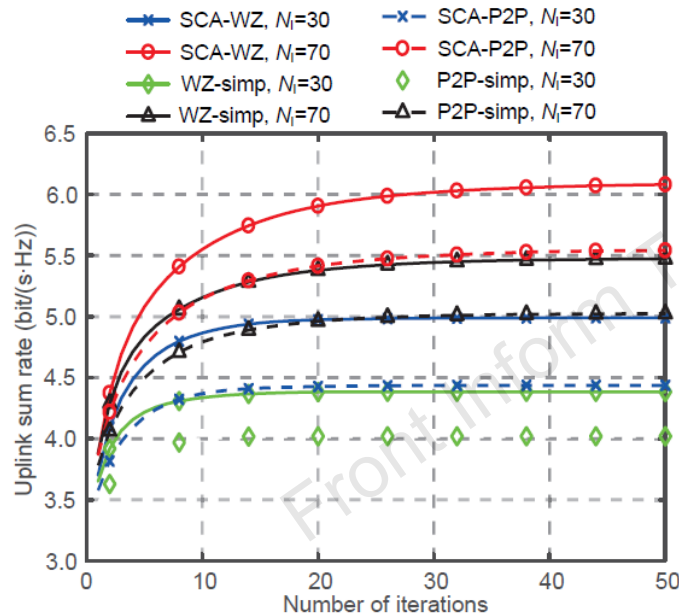


Fig. 2 Average sum rate versus the number of iterations ($P_k = 10$ dBm, $C_l = 5$ bits/(s·Hz), $\forall l$, $N_R = 4$, $N_U = 2$)

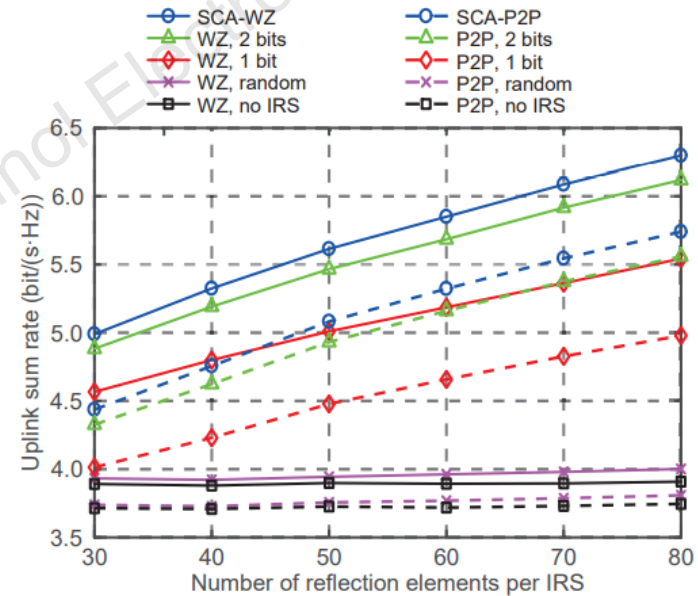


Fig. 3 Average sum rate versus the number of reflection elements per IRS ($P_k = 10$ dBm, $C_l = 5$ bits/(s·Hz), $\forall l$, $N_R = 4$, $N_U = 2$)

Major results (Cont'd)

Average sum rate versus the number of reflection elements per IRS and the number of RRH antennas

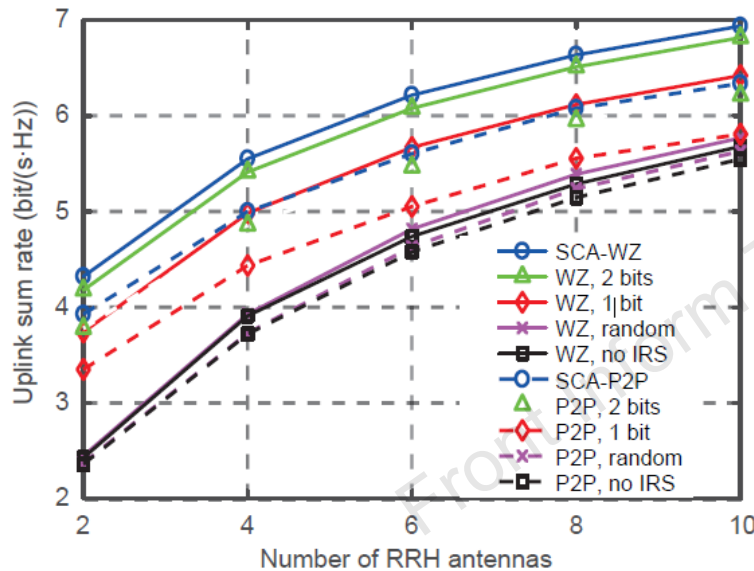


Fig. 4 Average sum rate versus the number of RRH antennas ($P_k = 10$ dBm, $N_I = 50$, $N_U = 2$, $C_I = 5$ bits/(s·Hz), $\forall l$)

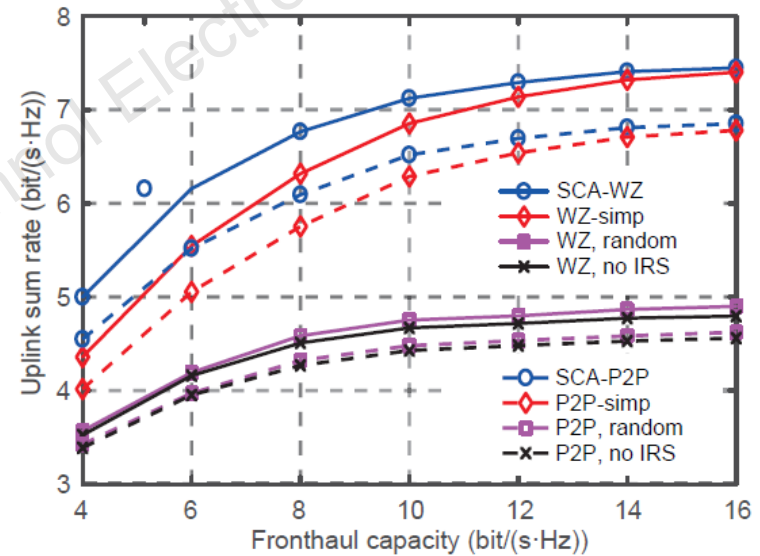
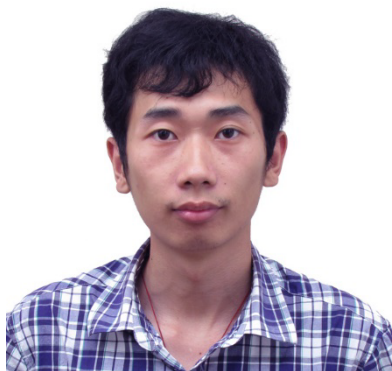


Fig. 5 Average sum rate versus the sum fronthaul capacity ($P_k = 10$ dBm, $N_I = 50$, $N_R = 4$, $N_U = 2$)

Conclusions

1. Deploying IRSs can considerably improve the C-RAN uplink sum rate with the proposed optimization algorithms. In addition, increasing the number of IRSs or the number of reflection elements per IRS can improve the performance.
2. The proposed algorithms for P2P compression and WZ compression outperform all the benchmark schemes. Therefore, both algorithms can effectively improve the system performance.
3. The proposed optimization algorithms converge in all cases and have a good convergence behavior.



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