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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

Corresponding author: Yu ZHANG
E-mail: yzhang@zjut.edu.cn
ORCID: https://orcid.org/0000-0002-9736-8244

Motivation

1. With the development of AI, IoT, mobile Internet, and industrial Internet, it is necessary to build intellicise (standing for 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.

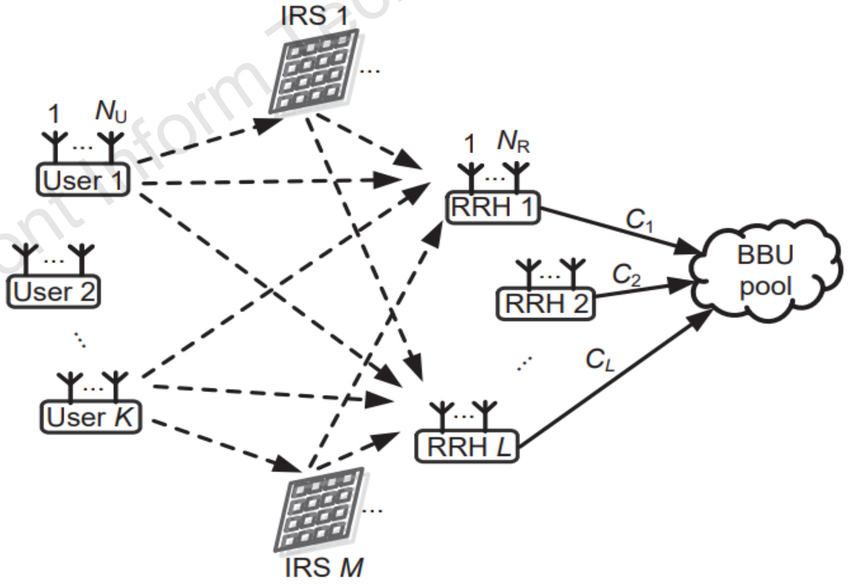


Fig. 1 System model

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：

$$\max_{\boldsymbol{F}_k,\boldsymbol{\Theta},\boldsymbol{\Omega}_l}\Big(\log_2|\boldsymbol{V}_{\mathcal{L}}\boldsymbol{F}_{\mathcal{K}}\boldsymbol{F}_{\mathcal{K}}^{\mathrm{H}}\boldsymbol{V}_{\mathcal{L}}^{\mathrm{H}}+\sigma^2\boldsymbol{I}+\boldsymbol{\Omega}_{\mathcal{L}}| \\ -\log_2|\sigma^2\boldsymbol{I}+\boldsymbol{\Omega}_{\mathcal{L}}|\Big)$$

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

Problem formulation (Cont’d)

For Wyner-Ziv coding compression:

$$\max_{\boldsymbol{F}_k,\boldsymbol{\Theta},\boldsymbol{\Omega}_{\mathcal{L}}} \Big(\log_2 \left| \boldsymbol{V}_{\mathcal{L}} \boldsymbol{F}_{\mathcal{K}} \boldsymbol{F}_{\mathcal{K}}^{\mathrm{H}} \boldsymbol{V}_{\mathcal{L}}^{\mathrm{H}} + \sigma^2 \boldsymbol{I} + \boldsymbol{\Omega}_{\mathcal{L}} \right| - \log_2 \left| \sigma^2 \boldsymbol{I} + \boldsymbol{\Omega}_{\mathcal{L}} \right| \Big)$$

$$\text{s.t.} \begin{cases} \log_2 \left| \boldsymbol{V}_{\mathcal{L}} \boldsymbol{F}_{\mathcal{K}} \boldsymbol{F}_{\mathcal{K}}^{\mathrm{H}} \boldsymbol{V}_{\mathcal{L}}^{\mathrm{H}} + \sigma^2 \boldsymbol{I} + \boldsymbol{\Omega}_{\mathcal{L}} \right| \\ \quad - \log_2 \left| \boldsymbol{V}_{\bar{\mathcal{S}}} \boldsymbol{F}_{\mathcal{K}} \boldsymbol{F}_{\mathcal{K}}^{\mathrm{H}} \boldsymbol{V}_{\bar{\mathcal{S}}}^{\mathrm{H}} + \sigma^2 \boldsymbol{I} + \boldsymbol{\Omega}_{\bar{\mathcal{S}}} \right| \\ \quad - \log_2 \left| \boldsymbol{\Omega}_{\mathcal{S}} \right| \le C_{\mathcal{S}},\ \forall \mathcal{S}, \\ \operatorname{tr}\left(\boldsymbol{F}_k \boldsymbol{F}_k^{\mathrm{H}} \right) \le P_k, \forall k \in \mathcal{K}, \\ \left| \theta_{m,n} \right| = 1, \forall m, n, \\ \boldsymbol{\Omega}_l \succeq 0, \forall l \in \mathcal{L}. \end{cases}$$

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

$$\max_{\boldsymbol{E}_l,\boldsymbol{W},\boldsymbol{\Sigma},\boldsymbol{F}_k,\boldsymbol{\Theta},\boldsymbol{\Omega}_l} \mathbb{E}\left[\log_2\left(\frac{\mathcal{CN}(\boldsymbol{W}\hat{\boldsymbol{y}}_{\mathcal{L}},\boldsymbol{\Sigma})}{\mathcal{CN}(\boldsymbol{0},\boldsymbol{I})}\right)\right]$$

$$\text{s.t.}\begin{cases}\log_2|\boldsymbol{E}_l| + \operatorname{tr}(\boldsymbol{E}_l^{-1}\boldsymbol{\Gamma}_l) - N_{\mathrm{R}} - \log_2|\boldsymbol{\Omega}_l| \le C_l,\\ \operatorname{tr}(\boldsymbol{F}_k\boldsymbol{F}_k^{\mathrm{H}}) \le P_k, \forall k \in \mathcal{K},\\ \boldsymbol{\Omega}_l \succeq 0, \forall l \in \mathcal{L},\\ |\theta_{m,n}| = 1, \forall m, n.\end{cases}$$

Method (Cont’d)

For the Wyner-Ziv coding compression:

$$\max_{\substack{\boldsymbol{W},\boldsymbol{\Sigma},\boldsymbol{E}_{\mathcal{L}},\boldsymbol{F}_k,\\ \boldsymbol{\Theta},\boldsymbol{\Omega}_{\mathcal{L}},\boldsymbol{W}_{\bar{\mathcal{S}}},\boldsymbol{\Sigma}_{\bar{\mathcal{S}}}}} \mathbb{E}\left[\log_2\left(\frac{\mathcal{CN}\left(\boldsymbol{W}\hat{\boldsymbol{y}}_{\mathcal{L}},\boldsymbol{\Sigma}\right)}{\mathcal{CN}\left(\boldsymbol{0},\boldsymbol{I}\right)}\right)\right]$$

$$\log_2\left|\boldsymbol{E}_{\mathcal{L}}\right|+\operatorname{tr}\left(\boldsymbol{E}_{\mathcal{L}}^{-1}\boldsymbol{\Gamma}_{\mathcal{L}}\right)-\mathbb{E}\left[\log_2\left(\frac{\mathcal{CN}\left(\boldsymbol{W}_{\bar{\mathcal{S}}}\hat{\boldsymbol{y}}_{\bar{\mathcal{S}}},\boldsymbol{\Sigma}_{\bar{\mathcal{S}}}\right)}{\mathcal{CN}\left(\boldsymbol{0},\boldsymbol{I}\right)}\right)\right]$$

$$-\log_2\left|\boldsymbol{\Omega}_{\mathcal{S}}\right|-\log_2\left|\sigma^2\boldsymbol{I}+\boldsymbol{\Omega}_{\bar{\mathcal{S}}}\right|-LN_{\mathrm{R}}\le C_{\mathcal{S}},\forall\mathcal{S},$$

$$\operatorname{tr}\left(\boldsymbol{F}_k\boldsymbol{F}_k^{\mathrm{H}}\right)\le P_k,\forall k\in\mathcal{K},$$

$$\boldsymbol{\Omega}_l\succeq 0,\forall l\in\mathcal{L},$$

$$\left|\theta_{m,n}\right|=1,\forall m,n.$$

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

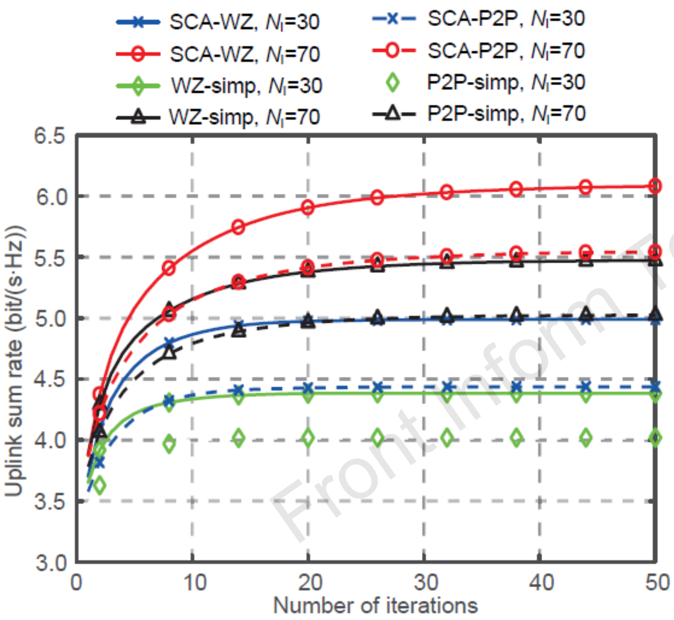


Fig. 2 Average sum rate versus the number of iterations (P_k =10 dBm, C_l =5 bits/(s·Hz), $\forall l$, $N_{\mathrm{R}} = 4$, $N_{\mathrm{U}} = 2$)

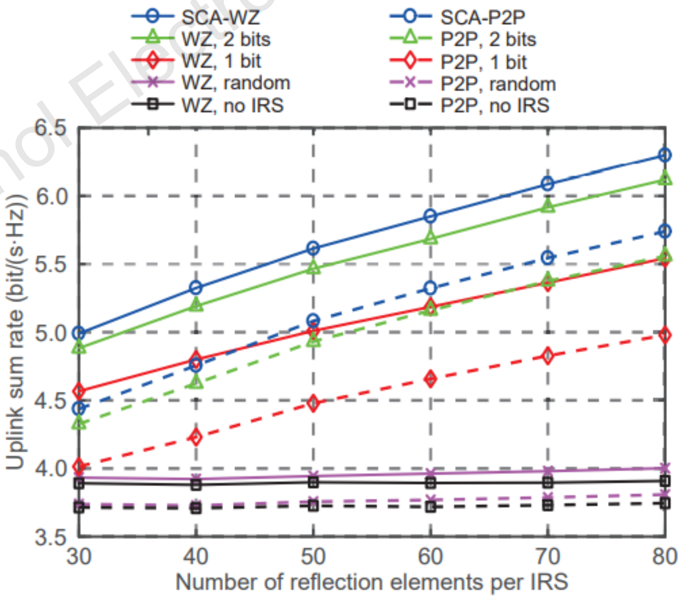


Fig. 3 Average sum rate versus the number of reflection elements per IRS (P_k =10 dBm, C_l = 5 bits/(s·Hz), $\forall l$, $N_{\mathrm{R}} = 4$, $N_{\mathrm{U}} = 2$)

Major results (Cont’d)

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

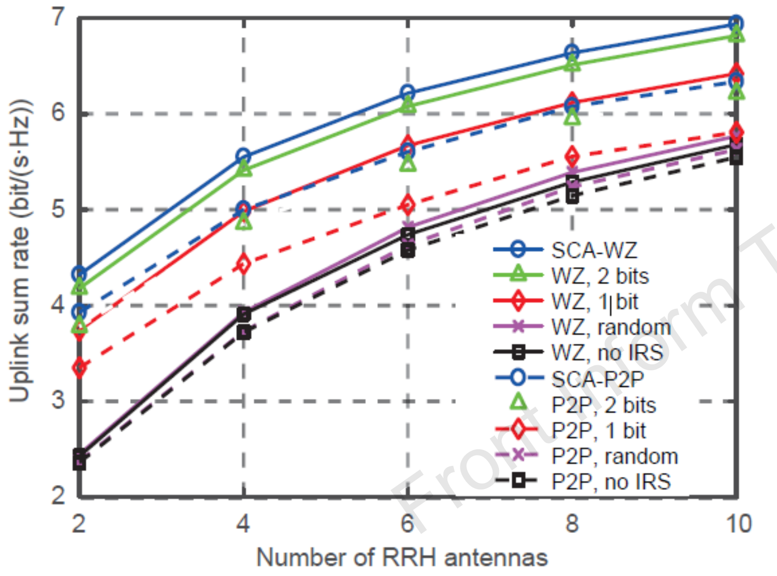


Fig. 4 Average sum rate versus the number of RRH antennas (P_k =10 dBm, N_I =50, N_U = 2, C_l =5 bits/(s·Hz), $\forall l$)

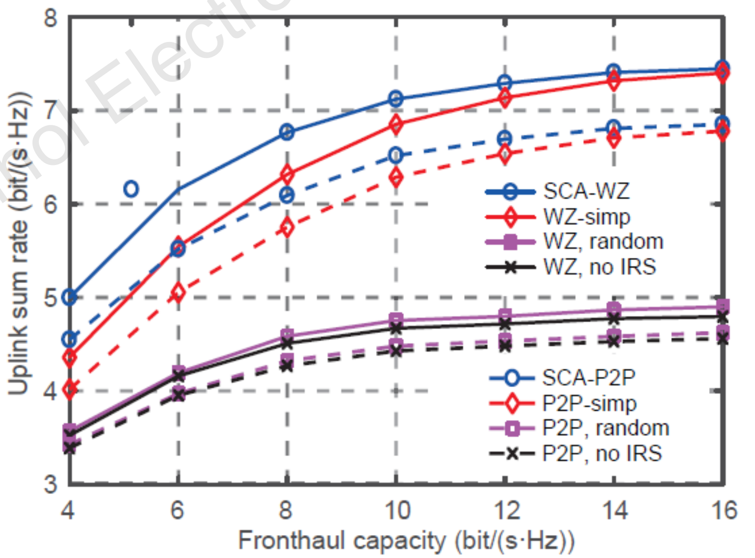


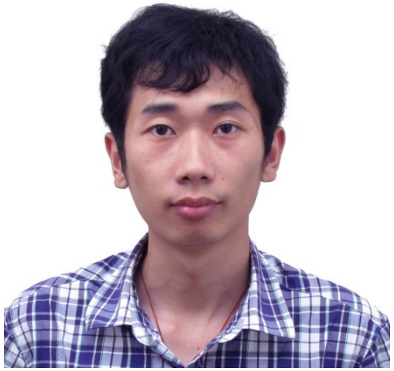
Fig. 5 Average sum rate versus the sum fronthaul capacity (P_k =10 dBm, N_I =50, N_R = 4, N_U = 2)

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.



张昱，浙江工业大学信息工程学院副教授。研究领域：云接入网、智能反射面、无速率编码等。已发表SCI论文20余篇，获得WiSATS2019最佳论文奖以及IEEE Globecom 2020最佳论文奖等奖励。获国家授权发明专利10余项。主持国家自然科学基金面上项目、青年基金，中国博士后科学基金，浙江省自然科学基金等项目。获浙江省通信学会科学技术奖三等奖、中国发明协会创业创新奖二等奖等奖励。长期担任国内外重要学术期刊审稿人以及学术会议TPC成员。