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Intelligent Reflecting Surface Aided Cloud Access Networks with Federated Learning

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Abstract

Compared with traditional cellular network architecture, cloud access network has some significant advantages in spectrum utilization, energy consumption and network construction cost. However, a high-quality forward link is required between the baseband processing unit pool and remote radio head (RRH) in the cloud access network, which results in limited RRH deployment and affects user access link transmission and coverage. To solve this issue, this paper introduces the intelligent reflector technology into the cloud access network as a solution with low energy consumption, low cost and easy deployment to deal with the existing bottlenecks. Firstly, an efficient channel information acquisition strategy based on federated learning is designed for the smart reflector to enhance the user access link, so as to achieve a compromise between the channel estimation accuracy and cost. On this basis, a robust beamforming design and optimization method of the compression mechanism of the forward link are proposed for the smart reflector to enhance the user access link and the wireless forward link, so as to improve the system transmission performance. Finally, we explore the joint resource allocation method of intelligent reflector assisted cloud access network, and improve the system energy efficiency through the collaborative configuration of intelligent reflector and cloud access network communication resources. The research of this paper will provide an important theoretical basis for the application of intelligent reflectors in cloud access networks, especially for the federated learning.

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1. Introduction

Starting from the first generation mobile communication system to the fifth generation mobile communication system commercially available today, communication has been maintaining rapid technological innovation. However, with the rapid growth of the number of mobile devices, the popularity and the rise of new applications, such as virtual reality and augmented reality, have put forward higher communication requirements for the current communication system, bringing urgent challenges [1].

To address the above challenges, optimizing and reconfiguring the existing access network architecture is an important direction [2]. Among them, a new type of access network architecture, i.e., cloud access network, has been proposed to gain a wide attention from academia and industry. Cloud access networks are ideally suited for deployment in scenarios with large-scale communication needs, such as large public places (including shopping malls, sports stadiums, etc.) and high-density urban areas [3]. The diversity of today's subscriber quality of service (QoS) requirements is also driving operators to centralize and cloudify the baseband processing units (BBUs) at each base station. The specific architecture of the cloud access network is shown in Figure 1, where the remote

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radio frequency unit (RRH) and BBU of each access node are separated [4], with the RRH closer to the user and the BBU set backward to the BBU pool, which is connected to the RRH by a forward link. Compared with the traditional cellular structure, a cloud access network has advantages in the following aspects. First, joint signal processing in the BBU pool is conducive to interference coordination and multipoint collaboration (CoMP), which can effectively improve spectrum efficiency and avoid frequent user switching in small base station systems [5]. Second, the cloud access network has a lower infrastructure cost, expanding the network only by the deployment of new RRH and laying the forward link. Finally, cloud access networks have a higher energy efficiency, compared with traditional cellular. RRHs are closer to users and require less transmission power, as the signal processing of each RRH is concentrated in the BBU pool, and energy consumption will also be much smaller than traditional cellular networks [6, 7].

The current cloud access network faces the following bottlenecks. On one hand, a forward link with a high transmission rate and high reliability is required between the BBU pool and the RRH [8, 9]. The traditional forward link uses a wired connection, such as optical fiber or cable. The wired forward link is not flexible enough in deployment. Some urban areas may not be suitable for laying wired links [10, 11]. With the increase of wired forward links, the network complexity of the forward link will increase exponentially. Based on the flexibility of wireless transmission, wireless forward link as an alternative has received extensive attention in recent years. However, due to wireless channel characteristics, interference, and other factors, the capacity and reliability of wireless forward links need to be improved urgently. On the other hand, the requirements for reliable and high-speed forward links limit the RRH deployment location and density, which in turn affects the transmission and coverage of user access links. Therefore, when providing services to hot spots in complex urban environments, cloud access networks still face challenges in user coverage and data transmission.

The intelligent reflector technology proposed in recent years is a low-cost and low-power solution to break through the above bottlenecks [12, 13]. The intelligent reflector is a reprogrammable passive reflection array technology, which can effectively improve the communication link quality and the communication system coverage by improving the electromagnetic wave propagation environment [14]. The intelligent reflector is arranged with a large number of passive reflection units made of metamaterials. The reflection characteristics (amplitude and phase) of each unit are digitally controllable and can form the desired reflection beam. Its mechanism is different from the reflection array antenna in radar systems and satellite communication, where the phase shift characteristics of each reflection unit of the traditional reflection array antenna are pre-designed and fixed. In contrast, the phase shift and amplitude imposed on the reflected wave by each reflection unit of the intelligent reflector can be adjusted in real-time. The intelligent reflector directly reflects the incident signal, and its effect is similar to the full-duplex multi-antenna amplification and forwarding relay. However, the smart reflector has no RF transmission link, has a lower cost and power consumption, does not actively forward signals, does not have full duplex self-interference, and does not introduce additional noise.

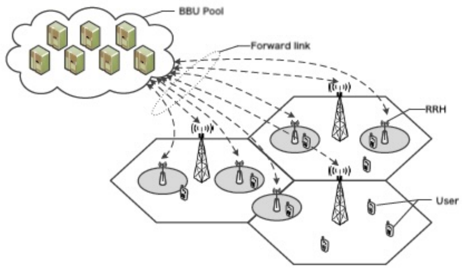

Figure 1. Traditional Cloud Access Network Architecture.

As shown in Figure 1, on one hand, the intelligent reflector can enhance the wireless forward link. By adjusting its reflection characteristics in real time, the link capacity and reliability can be improved. On the other hand, intelligent reflectors can help improve link capacity and enhance user coverage. Because only the reflection phase and amplitude need to be controlled, the transmission rate of the control link required by the intelligent reflector is very low. The intelligent reflector controller can be connected to the nearby BBU pool or RRH in wired or wireless mode. The intelligent reflector itself does not emit electromagnetic waves and does not require RF transmitting modules, so it has low power consumption and cost. At the same time, due to its passive characteristics and the far field effect, the interference between reflectors is much smaller than that of active communication nodes, and the secondary reflection between intelligent reflectors at a certain distance can be ignored. Therefore, it is feasible to deploy smart reflectors on large-scale cloud access networks.

2. Performance of smart reflective surfaces

Cloud access network has received extensive attention from academia and industry since it was proposed. The cloud access network architecture has evolved from the original completely centralized architecture to the current partially centralized architecture. For the former, RRH only retains basic RF functions (i.e. filter, power amplifier, digital to analog conversion, etc.), and centralizes all functions from the physical layer to the network layer into the BBU pool. The latter flexibly divides the functions of each layer between the RRH and BBU pool according to the practical needs. In recent years, in order to meet the growing communication demand and communication scenarios, cloud access network architectures are also constantly enriched, such as heterogeneous cloud access networks, virtual cloud access networks based on network function virtualization, and fog access networks that introduce edge computing.

On the other hand, in recent years, intelligent reflector technology has received a lot of attention from the academic community. A large number of reflective units are arranged on the surface of the intelligent reflector, and the external nodes (such as base stations) are communicated with the intelligent control module under the surface. The intelligent reflector can adjust each reflection unit in real time to change the response to the incident signal, that is, the amplitude and phase of the reflected signal. Its accuracy is limited by device technology and complexity. At present, there are many intelligent reflector implementation schemes. For example, the existing literature has built an indoor millimeter wave intelligent reflector platform, arranged two types of reflective units with different reflective phases on the reflector, and realized 1-bit phase control accuracy by controlling each reflective unit to switch between "reflective" and "absorbing" states. Intelligent reflector technology introduces a new dimension to enhance wireless communication systems. From the perspective of information theory, the traditional design idea of wireless communication is to optimize the distribution of input symbols while determining the channel transition probability. The introduction of an intelligent reflector makes the channel transition probability an optimization object.

Channel estimation is an important problem in the field of intelligent reflectors. If the intelligent reflector is equipped with an RF receiving module, the traditional channel estimation techniques can be used to directly estimate the channel. However, additional receiving modules will increase the cost and power consumption of the reflector. On the contrary, traditional channel estimation methods are no longer feasible. For smart reflector-assisted large-scale antenna systems, the existing literature proposed a two-stage channel estimation method by designing a pilot sequence and reflector pattern to obtain the channel information from the base station to the reflector and from the reflector to the user. On the other hand, by setting the reflection pattern of the reflector, such as ON/OFF pattern and DFT pattern, the equivalent cascade channel information of the reflection link can also be obtained as a substitute, which will not affect the subsequent system design. Considering the correlation of the channel between adjacent reflectors, the existing literature proposed a channel estimation method based on reflection unit grouping to reduce the overhead. For multi-user intelligent reflector systems, existing literature has proposed a phased channel estimation method, which can effectively reduce redundant channel estimation, considering that the reflector to access point link is a common link and changes slowly for each user.

In the cloud access network, the BBU pool needs to obtain the channel status of each user to each RRH for CoMP transmission and interference coordination. When the number of users is large, it requires a large channel overhead. The existing literature has studied the reuse and allocation of training sequences and the corresponding beamforming optimization methods for dense user scenarios. In addition, since the channel estimation is performed in the BBU pool, the impact of the forward link on the training sequence compression needs to be considered. The power allocation between the pilot signal and data signal under the distortion of the training sequence has been studied in the existing literature. After the intelligent reflector is introduced into the cloud access network, the BBU pool needs to obtain not only the channel information of the direct link, but also the channel information of the reflection link between each user and each RRH through each reflector, which will significantly increase the difficulty and cost of channel estimation. In addition, the compression of pilot signals in the forward link transmission will also affect the acquisition of channel information. Therefore, in the cloud access network assisted by intelligent reflectors, how to obtain channel information efficiently and achieve a compromise between the accuracy and cost is worth an in-depth study.

Efficient forward link compression and beamforming design are key issues in cloud access networks, and they are coupled. Starting from the network information theory, the existing literature gives the theory and optimization framework of forwarding link compression transmission. In addition to point-to-point compression, RRH can implement distributed compression based on Wyner-Ziv coding for uplink transmission. For downlink transmission, the BBU pool can use multivariable compression to achieve a better compression performance. For uplink transmission, the forward link compression is affected by the joint statistical characteristics of the upstream received signals of each RRH, so the forward link compression and user beamforming are coupled. The existing literature has studied the joint optimization of user beamforming and RRH signal compression noise covariance matrix. In downlink transmission, the user receives the sum of the useful signals from each RRH and the forward compression noise. Therefore, RRH beamforming and forward link compression both affect the user's reception performance. According to the existing literature, we should study the joint design of RRH beamforming, forward link compression, and coded transmission for multi-user downlink transmission in the cloud access network. The existing literature jointly optimizes the covariance matrix of downlink beamforming and forward compression noise. When the current transmission link adopts a wireless connection, the forward link capacity is related to the RRH and BBU pool beamforming. The existing literature has studied the joint design of forwarding links, access link beamforming, and forward compression to maximize the sum rate under RRH decoding forwarding or decompression forwarding. The existing literature has studied the joint design optimization of wireless forward links and access links under multi-RRH clustering.

On the other hand, the intelligent reflector allocates the wireless propagation environment by adjusting the reflection amplitude and phase of each unit, that is, the passive wave forming. The characteristics of reflector devices make their beamforming design significantly different from the traditional multi-antenna system. The existing literature has studied the downlink single-user transmission scenarios with multiple antennas, and jointly optimized the AP to form the reflector beam. According to the existing literature, we should further consider the robust transmission under channel estimation error. The existing literature has studied the beamforming design of AP and reflectors under multi-antenna downlink multi-user transmission. The existing literature has studied the joint design of power control, multi-user detection, and reflector phase shift matrix for multi-user uplink transmission assisted by intelligent reflectors. In the existing literature, the researchers have studied the joint optimization of the source node and reflector beamforming for intelligent reflector-assisted full-duplex bidirectional transmission. The existing literature has studied the joint optimization problem of cooperative transmission of multiple intelligent reflection. In an intelligent reflector-assisted cloud access network, the access link between users and RRH, and the wireless forward link channel status between RRH and BBU pools can be controlled through reflector beamforming. Therefore, for the design of mutual coupling users, RRH, BBU pool beamforming, and forward link compression in the cloud access network, it is necessary to further jointly consider the design of the auxiliary forward link and the reflector beamforming based on the incoming link to optimize the transmission performance. How to design an effective and robust optimization method is of great research significance.

In cloud access networks, due to the limitations of user access link capacity, forward link capacity, and transmit power, all users cannot be served simultaneously on the same time-frequency block, and better system performance can be obtained by selecting users with a better channel quality. Each user can only be served by some of the RRHs due to factors such as forward link capacity limitation, BBU pool signal processing complexity, and channel information acquisition overhead. The existing works have jointly optimized the forward link beamforming as well as access user clustering under multicast beamforming for the forward link. Some researches have jointly optimized the forward link and access link beamforming as well as user RRH association to maximize the sum rate for the RRH using a decode-and-forward case. In addition, considering the energy consumption and channel estimation overhead associated with RRH, the joint optimization of RRH selection and beamforming with guaranteed user QoS has been investigated to minimize the system energy consumption. The optimization of user scheduling, RRH user association, forward link, and access link with beamforming and RRH switching strategies have been jointly considered under the condition of incomplete channel state information. In addition, for full-duplex RRH cloud access networks, RRH beamforming and user power allocation optimization to minimize network energy consumption have been studied in the literature, and the user selection issues involved have been further considered in the literature. In a smart reflector-assisted cloud access network, reflector switching and beamforming will affect the channel state of its auxiliary link. Similar to RRH, turning on the smart reflector also brings additional energy consumption and channel estimation overhead. This introduces new configurable factors for user scheduling, user RRH association, and provisioning of communication resources in traditional cloud access networks. Therefore, it is worthwhile to conduct further research on how to design effective resource provisioning methods for intelligent reflective surface-assisted cloud access networks to optimize system energy efficiency.

Up to now, there are few works related to intelligent reflector-assisted cloud access networks. The existing literature has studied the use of intelligent reflectors to enhance the performance of air computing in cloud access networks. The existing literature has studied the beamforming design in the smart reflector-enhanced cell-free network to improve the transmission rate and energy efficiency of the system. Under the ideal channel information, we have conducted some preliminary research on the beamforming and forward compression design of intelligent reflector-enhanced cloud access network transmission. It can be seen that the research on intelligent reflector-assisted cloud access networks is in its infancy, and many key theories and technologies need to be broken through.

3. System design and analysis

The channel estimation performance function $f_i(\mathbf{p}, \beta, \mathbf{\Omega})$ is related to the following variables: $\mathbf{p}$ denotes the set of user transmit power, β denotes the set of user/reflecting surface/RRH large-scale fading values, and $\mathbf{\Omega}$ denotes the set of RRH forward link noise covariance matrix, which is related to the forward link capacity. The problem of minimizing the required power while satisfying the estimation accuracy requirements for each user channel can be modeled as,

$$\begin{aligned} &\max_{\mathbf{p}} \textstyle\sum_k p_k \\ &\text{s.t. } f_k(\mathbf{p}, \beta, \mathbf{\Omega}) \le \eta_k, \forall k \end{aligned} \tag{1}$$

where η_k is the estimation error threshold. The above problem is relevant to the training sequence power allocation problem in non-orthogonal access systems.

For the auxiliary access link of the intelligent reflector, take the uplink transmission as an example, and the transmission model is,

$$\mathbf{y}_i^{ul} = (\mathbf{H}_{d,i} + \mathbf{G}_i \mathbf{\Theta} \mathbf{H}_u) \mathbf{F}\mathbf{s} + \mathbf{n}_i, \tag{2}$$

where $\mathbf{y}_i^{ul}$ is the i-th RRH received signal, $\mathbf{H}_{d,i}$, $\mathbf{H}_w$, and $\mathbf{G}_i$, are the channel matrices from the user to the i-th RRH, the user to the reflecting surface, and the reflecting surface to the i-th RRH, respectively. Notation $\mathbf{F}$ is the block diagonal array composed of the beamforming matrices of each user, $\mathbf{\Theta}$ is the diagonal array composed of the beamforming matrices of all reflecting surfaces, and s is the set of all user transmitted signals, and $\mathbf{n}_i$ is the Gaussian noise. From (2), we can have,

$$I\left(\mathbf{y}_i^{ul}; \hat{\mathbf{y}}_i^{ul}\right) \le C_i. \tag{3}$$

With the objective of maximizing the uplink transmission rate, the following optimization problem can be obtained by jointly optimizing the user/reflective plane beamforming and the forward link compression noise covariance matrix:

$$\begin{aligned} &\max_{\mathbf{\Theta}, \{\Omega_i^{ul}, \{\mathbf{F}_i\}} \quad R^{ul} = I\left(\mathbf{s}; \hat{\mathbf{y}}^{ul}\right), \\ &s.t. \quad I\left(\mathbf{y}_i^{ul}; \hat{\mathbf{y}}_i^{ul}\right) \le C_i, \forall i; \mathrm{Tr}\left(\mathbf{F}_l \mathbf{F}_l^H\right) \le P_u, \forall l, \end{aligned} \tag{4}$$

where $\hat{\mathbf{y}}^{ul}$ is the set of all $\mathbf{y}_i^{ul}$ and $\mathbf{F}_l$ is the beamforming matrix for each user.

Further considering the wireless forward link, for the above example, the transmission model of the forward link with the assistance of the intelligent reflective surface is,

$$\mathbf{y}^{ful} = \sum_{i=1}^{K} \left(\mathbf{H}_{f,i} + \mathbf{G}_f \mathbf{\Theta}_f \mathbf{H}_{r,i}\right) \mathbf{F}_{f,i} \mathbf{s}_{f,i} + \mathbf{n}, \tag{5}$$

where $\mathbf{y}^{ful}$ is the BBU pool received signal, $\mathbf{H}_{f,i}$, $\mathbf{H}_{r,i}$ and $\mathbf{G}_f$ are the channel matrices from the i-th RRH to the BBU pool, the i-th RRH to the reflecting surface, and the reflecting surface to the BBU pool, respectively. Notations $\mathbf{F}_{f,i}$ and $\mathbf{\Theta}_f$ are the RRH and reflecting surface beamforming matrices, respectively, and $\mathbf{s}_{f,i}$ is the RRH transmission data symbol. The forward link capacity of each RRH should be in the capacity area of the multi-user access channel (5), given by,

$$\sum_{i=S} C_i \le I\left(\mathrm{s}_{f,S}; \mathrm{y}^{fui} \mid \mathrm{s}_{f,S}\right), S \subseteq \{1, 2, \ldots, K\} \tag{6}$$

where K is the total number of RRHs. The resulting extension of the optimization problem in (4) requires additional consideration of the optimization variables $\mathbf{F}_{f,i}$ and $\mathbf{\Theta}_f$, along with the inclusion of the forward link constraint in (6). Similar to the access link, $\mathbf{F}_{f,i}$ and $\mathbf{\Theta}_f$ are coupled in the form of a product and need to be decoupled using the alternating optimization method.

4. Conclusion

In summary, smart reflective surfaces can break through the current bottlenecks of cloud access networks by enhancing the radio forward link as well as the user access link, further enhancing the spectrum efficiency, energy efficiency, reliability, and flexibility of cloud access networks. The introduction of intelligent reflective surfaces makes the channel state of communication links a modifiable variable, which introduces new design dimensions and challenges for transmission design and resource optimization in traditional cloud access networks. In this paper, three aspects of channel information acquisition, transmission optimization, and joint resource provisioning were studied to obtain a complete set of theories and techniques for intelligent reflective surface-enhanced cloud access networks, especially for the application of federated learning.

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4.2. Copyright

References

[1] J. Lu, S. Lai, J. Xia, M. Tang, C. Fan, J. Ou, and D. Fan, "Performance analysis for irs-assisted mec networks with unit selection," *Physical Communication*, vol. 55, p. 101869, 2022.

[2] L. Zhang, S. Lai, J. Xia, C. Gao, D. Fan, and J. Ou, "Deep reinforcement learning based irs-assisted mobile edge computing under physical-layer security," *Physical Communication*, p. 101896, 2022.

[3] Y. Wu, J. Xia, C. Gao, J. Ou, C. Fan, J. Ou, and D. Fan, "Task offloading for vehicular edge computing with imperfect csi: A deep reinforcement approach," *Physical Communication*, vol. 55, p. 101867, 2022.

[4] D. Cai, P. Fan, Q. Zou, Y. Xu, Z. Ding, and Z. Liu, "Active device detection and performance analysis of massive non-orthogonal transmissions in cellular internet of things," *Science China information sciences*, vol. 5, no. 8, pp. 182 301:1–182 301:18, 2022.

[5] B. Wang, F. Gao, S. Jin, H. Lin, and G. Y. Li, "Spatial- and frequency-wideband effects in millimeter-wave massive MIMO systems," *IEEE Trans. Signal Processing*, vol. 66, no. 13, pp. 3393–3406, 2018.

[6] X. Hu, C. Zhong, Y. Zhu, X. Chen, and Z. Zhang, "Programmable metasurface-based multicast systems: Design and analysis," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1763–1776, 2020.

[7] X. Hu, C. Zhong, Y. Zhang, X. Chen, and Z. Zhang, "Location information aided multiple intelligent reflecting surface systems," *IEEE Trans. Commun.*, vol. 68, no. 12, pp. 7948–7962, 2020.

[8] S. Sheikhzadeh, M. Pourghasemian, M. R. Javan, N. Mokari, and E. A. Jorswieck, "Ai-based secure NOMA and cognitive radio-enabled green communications: Channel state information and battery value uncertainties," *IEEE Trans. Green Commun. Netw.*, vol. 6, no. 2, pp. 1037–1054, 2022. [Online]. Available: https://doi.org/10.1109/TGCN.2021.3135479

[9] X. Liu, C. Li, S. S. Ge, and D. Li, "Time-synchronized control of chaotic systems in secure communication," *IEEE Trans. Circuits Syst. I Regul. Pap.*, vol. 69, no. 9, pp. 3748–3761, 2022. [Online]. Available: https://doi.org/10.1109/TCSI.2022.3175713

[10] Z. Cao, X. Ji, J. Wang, W. Wang, K. Cumanan, Z. Ding, and O. A. Dobre, "Artificial noise aided secure communications for cooperative NOMA networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 8, no. 2, pp. 946–963, 2022. [Online]. Available: https://doi.org/10.1109/TCCN.2021.3130979

[11] G. Sun, J. Li, A. Wang, Q. Wu, Z. Sun, and Y. Liu, "Secure and energy-efficient UAV relay communications exploiting collaborative beamforming," *IEEE Trans. Commun.*, vol. 70, no. 8, pp. 5401–5416, 2022. [Online]. Available: https://doi.org/10.1109/TCOMM.2022.3184160

[12] L. Xiao, H. Li, S. Yu, Y. Zhang, L. Wang, and S. Ma, "Reinforcement learning based network coding for drone-aided secure wireless communications," *IEEE Trans. Commun.*, vol. 70, no. 9, pp. 5975–5988, 2022. [Online]. Available: https://doi.org/10.1109/TCOMM.2022.3194074

[13] M. Stute, F. Kohnhäuser, L. Baumgärtner, L. Almon, M. Hollick, S. Katzenbeisser, and B. Freisleben, "RESCUE: A resilient and secure device-to-device communication framework for emergencies," *IEEE Trans. Dependable Secur. Comput.*, vol. 19, no. 3, pp. 1722–1734, 2022. [Online]. Available: https://doi.org/10.1109/TDSC.2020.3036224

[14] J. Zhao, Q. Li, Y. Gong, and K. Zhang, "Computation offloading and resource allocation for cloud assisted mobile edge computing in vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 7944–7956, 2019.