On the Performance of UAV-Assisted IRS-NOMA Networks

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Abstract: In order to further improve the spectral efficiency of the communication system, we introduce the non-orthogonal multiple access (NOMA) technique into the UAV-IRS system. Specifically, a UAV-IRS communication system model using the NOMA scheme is first proposed. Then a physical-optics based IRS path loss model is used to derive the received signal-to-noise ratio and ergodic capacity formulas under the two-user scenario. Finally, we compare the total user capacity of the proposed system under the OFDMA scheme with the NOMA scheme. The numerical results show that the NOMA scheme improves the total user capacity by almost two times compared to the OFDMA scheme, and the area of the IRS is found to have a significant impact on the system performance.

1 INTRODUCTION

In the face of major natural disasters and emergencies, effective emergency communication is of great significance to improve rescue efficiency and safeguard people's lives. When an accident or disaster occurs, local fixed base stations usually cannot be used normally, while UAV-based relays (unmanned aerial vehicles) in next-generation communication systems have better flexibility, especially for remote areas or areas lacking base station facilities. UAV-based air relay can be quickly built. Therefore, UAVs make an important contribution to the orderly response to emergencies and reduce their harm as much as possible. In response to the problem of scarce spectrum resources and the destruction of base stations in emergency communication scenarios, it is important to improve the spectrum efficiency of UAVs.

Non-orthogonal multiple access (NOMA) technology is considered as a key technology for 5G and even next-generation wireless communication systems because of its high spectral efficiency and good fairness. In power domain NOMA systems, users with good channel conditions are assigned lower power allocation factors, while users with poor channel conditions are assigned higher power allocation factors. At the receiver side, SIC (successive interference cancellation) technique is used to eliminate the interference of part users and to realize more users in the same time frequency domain multiplexing, thus improving the spectral efficiency.

The introduction of power domain NOMA into UAV relay systems allows the full utilization of power domain resources, thus ensuring better transmission of signals (downlink) from the ground base station for ground users or better transmission of signals (uplink) from the base station for ground users.

The application of IRS in NOMA has been discussed by scholars (Z. Ding, 2020) (M. Fu, 2019). In (Z. Ding, 2020) explored the trade-off between reliability and complexity of relaying and IRS. The work in (M. Fu, 2019) jointly optimizes transmit beamforming and IRS phase shift matrix to minimize the transmission power of the base station. Related studies under large-scale MIMO-NOMA systems have been conducted in (L. Dai, 2019) (W. Hao, 2017) (B. Wang, 2017) (W. Yuan, 2017) (Y. Zhao, 2017). The work in (L. Dai, 2019) maximizes the total

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achievable user rate by jointly optimizing the allocated power and the power splitting factor, while guaranteeing the user base reception rate and power. The energy efficiency of large-scale MIMO-NOMA systems is maximized by optimizing the power allocation in (W. Hao, 2017). In (B. Wang, 2017), NOMA is used for the first time in beam-space MIMO to maximize the total user achievable rate through power allocation. NOMA is applied to HP precoding structures under large-scale MIMO systems in order to improve the system performance by exploiting the characteristics of NOMA in (W. Yuan, 2017). Total achievable user rate is maximized by designing digital precoding in (Y. Zhao, 2017).

Studies on UAV-NOMA systems, classified by channel characteristics, mainly include air-to-ground (A2G, air to ground) channels, Nakagami-m fading channels, path loss channels, and Rice channels. In (M. F. Sohail, 2018), the author investigates the sum-rate maximization problem in different urban environments and also compares the effect of fixed and dynamic UAV heights to reduce energy consumption with the UAV-NOMA system considering A2G channels. Under the same model, the work in (M. F. Sohail, 2019) considers the multi-user quality of service constraint and equates the energy efficiency maximization problem to a nonlinear fractional programming problem, where the user grouping scheme in channel conditions is considered. For UAV-NOMA systems considering Nakagami-m fading channels, a UAV-centric offload operation strategy and a user-centric emergency communication strategy are proposed for dense networks and scenarios where all users need to be served simultaneously in order to improve the system coverage probability in (T. Hou, 2019). In (T. Hou, 2019), the effect of LoS links and NLoS (non-line of sight) links is considered, and a stochastic geometric model is used to model the location of users and UAVs, and a closed-form expression for the system outage probability and traversal rate is derived. For the LoS link and NLoS link scenarios, the work in (M. Liu, 2020) first determines the user grouping scheme based on the access priority, then uses a message passing algorithm for sub-channel assignment, and finally jointly optimizes the transmit power of the UAV-NOMA system.

Most of the above works on the IRS-NOMA system do not consider the path loss model, but only focus on the small-scale fading model. The UAV system is mainly affected by the line of sight (LoS) link, so the conventional Rayleigh fading is not suitable for representing its channel characteristics. Importantly, the conjecture in (E. Basar, 2019) that the received power would be proportional to $1/(d+r)^2$. That conjecture might hold for an infinitely large IRS or in the near-field, if the IRS is configured to act as a mirror, but probably not in the far-field setup studied herein. In particular, one cannot use multiple infinite-sized IRS as in (E. Basar, 2019). So we use a pathloss model based on physical optics techniques for an IRS that is configured to reflect an incoming wave from a far-field source towards a receiver in the far-field to study the performance of our proposed system.

Although UAV-IRS and NOMA have been studied in great detail, for all I know, system combining the two together has not been studied yet. UAV-IRS can provide additional flexibility to communication systems, improve service coverage, and avoid service blind spots. Meanwhile, IRS as a passive relay can alleviate the technical problem of limited energy due to UAV battery limitations. And the introduction of power domain NOMA can further ensure the quality of service for edge users, thus improving the average system performance.

This paper mainly studies the system performance of the UAV-assisted IRS-NOMA communication system. We compare the results with the OFDMA method and verify that the UAV-assisted IRS-NOMA communication system has obvious advantages over OFDMA in terms of spectral efficiency and communication capacity. The main contributions of this paper are as follows:

(1) An IRS-NOMA communication network model based on UAV assistance is developed for the case of multiple groups of users in a single cell of the downlink. An UAV acts as an airborne passive relay station equipped with an IRS and serves multiple ground users, which are evenly divided into groups. According to the traditional IRS-NOMA system setup, we assume that the number of users in each group is 2, i.e., each group contains only one near-end user and one far-end user.

(2) When considering the path loss model, in order to further explore the communication performance of the UAV-assisted IRS-NOMA system, we consider both large-scale fading and small-scale fading. The IRS path loss model based on the physical optics negates a past erroneous path loss model (Özdogan, 2020). In terms of small-scale fading, we adopt the LoS fading channel setup commonly used in traditional UAV wireless communication systems.

(3) To verify the performance of our proposed system, we compare the system with NOMA scheme

and the system with OFDMA scheme. The formulas of the receiver SNR and throughput of the two schemes are deduced respectively. The numerical results show that under the same system settings, the NOMA scheme has a greater improvement compared to the OFDMA scheme.

The rest of this paper is organized as follows. In Section 2, we introduce the system model. In Section 3, we use a pathloss model based on physical optics to derive the SNR and the capacity of users. In Section 4, numerical results are provided to demonstrate the performance of proposed system. Conclusions are presented in Section 5.

2 SYSTEM MODEL

Consider a downlink UAV-NOMA system as shown in Fig.1. The system consists of a ground base station with a single antenna, fixed at a specified altitude H_{BS}. An UAV equipped IRS operates at a specified location and the ground coverage of it is a circle of radius R. Furthermore, the system has M single-antenna terrestrial users. Assuming that M users are divided into T groups, each group has 2 users denoted as u_k, the set of group numbers is defined as $t \epsilon \{1,2,\dots,T\}$ and the set of user serial numbers is $k \epsilon \{1,2\}$. $u_1$of all groups are uniformly distributed in circles with radius r_1, while u_2 of all groups are uniformly distributed in Distributed within a circle of outer radius r_2 and inner radius r_1, where $r_1 < r_2$. In addition, users in a group share the same time-frequency domain resources by using the power domain NOMA technology, and orthogonal multiple access (OMA, orthogonal multiple access) is maintained between each group, that is, inter-group interference is ignored. Set up a three-dimensional Cartesian coordinate system as shown in Fig.1, with the base station as the coordinate origin, perpendicular to the ground as the z-axis, and the line between the base station and the projection of UAV on the ground as the x-axis. Then the coordinates of the transmitter are (0, 0, H_{BS}), and the coordinates of the UAV are (x_{UAV}, 0, H_{UAV}) (H_{UAV}> H_{BS}).

The base station transmits a signal x_k to user k, where $E[|x_k|^2]=1$, with transmission power P_k. The sum of P_k is restricted to P at maximum. In the NOMA, x_1 and x_2 are superposition coded as (Y. Saito, 2013)

$$x = \sqrt{P_1}x_1 + \sqrt{P_2}x_2 \qquad (1)$$

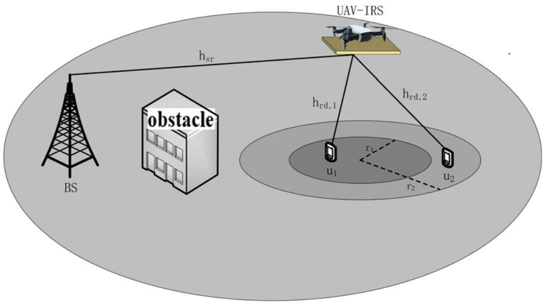

Figure 1: A system diagram for UAV-IRS under two-user scenario

We consider the UAV to carry a rectangular, perfectly conductive IRS plate of size $a \times b$ with negligible thickness, lying in a horizontal plane (spanned by e_x, e_y). For the sake of argument, we assume that the polarization of the source is such that the electric field is parallel to e_x and the H field lies in the plane spanned by e_y and e_z. Let $\theta_i \in [0, \pi/2]$ denote the angle of incidence, that is, the angle between the Poynting vector of the wave and e_z. The setup is shown in Fig.2. When including the reflected path from the IRS, we get the received signal as:

$$G = \left(\sqrt{I_{IRS}^{S}} h_{sr}^{T} \Phi h_{rd}\right) x + \omega \qquad (2)$$

We use a pathloss model based on physical optics techniques for an IRS that is configured to reflect an incoming wave from a far-field source towards a receiver in the far-field which is illustrated in Fig.2. The pathloss can be expressed as:

$$I_{IRS}^{s} = \frac{G_t G_r}{(4\pi)^2} \left(\frac{ab}{N_a N_b dr}\right)^2 \cos^2(\theta_i) \qquad (3)$$

where$\theta_i \in [0, \pi/2]$ denote the angle of incidence, a and b is the width and the length of the IRS. Suppose the IRS consists of $N_a \times N_b = N$ elements, each having the size a $a/N_a \times \mathrm{b}/N_b$. d and r are the distance between the source and the IRS and the distance between IRS and the user. $h_{sr} = [\mathrm{e}^{j\Psi_1^{sr}}, \dots, \mathrm{e}^{j\Psi_n^{sr}}, \dots, \mathrm{e}^{j\Psi_N^{sr}}]^T$ and $h_{rd} = [\mathrm{e}^{j\Psi_1^{rd}}, \dots, \mathrm{e}^{j\Psi_n^{rd}}, \dots, \mathrm{e}^{j\Psi_N^{rd}}]^T$ are the normalized LoS channels between the source and IRS and the IRS and receiver, respectively. $\omega \sim N(0, \sigma^2)$ is additive noise, and the surface phases of each surface element are stacked in $\Phi = \mathrm{diag}(\mathrm{e}^{\mathrm{j}\phi_1}, \dots, \mathrm{e}^{\mathrm{j}\phi_n}, \dots, \mathrm{e}^{\mathrm{j}\phi_N})$, which is a diagonal matrix.

An equivalent way to write the received signal is

$$G = \sqrt{I_{IRS}^{s}}\left(\sum_{n=1}^{N} \mathrm{e}^{j(\phi_n-\psi_n^{sr}-\psi_n^{rd})}\right)x+\omega \tag{4}$$

The IRS can select Φ to keep the received signal power maximum. It can be easily seen from the expression that the optimal choice of ϕ_n which maximizes the instantaneous SNR is $\phi_n = \psi_n^{sr} + \psi_n^{rd}$. Notably, this requires the channel phases are known to the RIS. When phase-align all the terms in (4), received signal can be simplified to $G = N\sqrt{I_{IRS}^{s}}x + \omega$ and the signal-to-noise ratio (SNR) can be obtained is

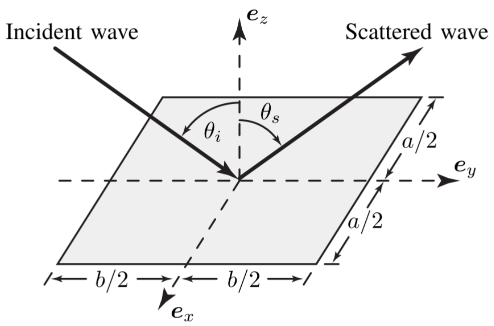

Figure 2: An incident wave is reflected by a × b IRS.

$$SNR = \frac{\left(N\sqrt{I_{IRS}^{s}}\right)^2 P_t}{\sigma^2} = \frac{IP_t}{\sigma^2} \tag{5}$$

In the NOMA scenario, the successive interference cancellation (SIC) process is implemented at the receiver. The optimal order for decoding is in the order of the increasing channel gain normalized by the noise and inter-cell interference power. Based on this order, any user can correctly decode the signals of other users whose decoding order comes before that user for interference cancellation. Thus, in the two-user case, the closer user can remove the inter-user interference from the farther user whose receive power is lower. The farther user does not perform interference cancellation since it comes first in the decoding order. Denote the closer user as u_1, the farther user as u_2. Then we can obtain the signal-interference-to-noise ratio (SINR) of the u_1:

$$SINR_1 = \frac{I_1P_1}{\sigma^2} \tag{6}$$

the signal-interference-to-noise ratio (SNR) of u_2 is

$$SINR_2 = \frac{I_2P_2}{I_2P_1+\sigma^2} \tag{7}$$

Assuming that the overall system transmission bandwidth is 1 Hz. The throughputs of two users are represented as

$$R_1 = log_2(1 + SINR_1) \tag{8}$$

$$R_2 = log_2(1 + SINR_2) \tag{9}$$

In the OFDMA with orthogonal user multiplexing scenario, where the bandwidth of $\alpha(0 < \alpha < 1)$Hz is assigned to u_1 and the remaining bandwidth, $1-\alpha$Hz, is assigned to u_2, the throughputs of two users are represented as

$$R_1 = \alpha\, log_2(1 + SINR_1) \tag{10}$$

$$R_2 = (1-\alpha)\, log_2(1 + SINR_2) \tag{11}$$

3 NUMERICAL RESULTS

In this section, computer simulation results are presented to demonstrate the performance of UAV-IRS under OFDMA scheme and NOMA scheme. In Fig.3, the performance of UAV-IRS is studied by focusing on the two-user case. Assuming that the height of the base station H_{BS} is 15m, and the UAV which carries a square IRS with a side length of 1m is fixed at (20,0,15). The gain of one-antenna transmission and one-antenna reception are G_t=15dBi and G_r=10dBi. Total transmission power is P=60dBm. The bandwidth of both schemes is 1Hz. In the OFDMA scheme, when equal bandwidth and equal transmission power are allocated to each user, the user rates are calculated according to (10) and (11) as R_1=1.4555 bps/Hz and R_2=0.9446 bps/Hz, respectively. On the other hand, in the NOMA scheme, when the power allocation is inversely proportional to the distance from the user to the IRS, the user rates are calculated according to (8) and (9) as R_1=1.7660 bps/Hz and R_2=1.2921 bps/Hz, respectively. The corresponding gains of NOMA comparing with OFDMA are 21% and 37% for u_1 and u_2, respectively.

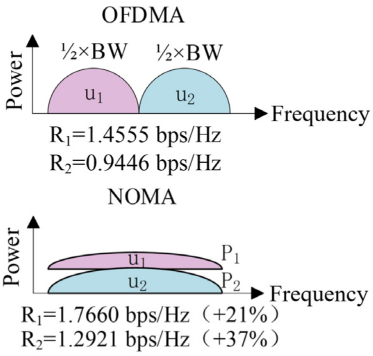

Figure 3: OFDMA vs. NOMA (two-user case).

Fig.4 showed that the total user rate of the proposed UAV-IRS under multi-group of user scenarios. Assuming the total bandwidth is 200MHz. The cell radius of the users is set to r_1=30m, r_2=100m. In the OFDMA scheme, all users share bandwidth equally. In the NOMA scheme, all user groups (each group includes two users) share bandwidth equally. Other settings are the same as before. As can be seen in Fig.4, when the number of users increases from 10 to 60, we find that there is almost a two-fold gain when comparing the total user rate under the NOMA scheme with the total user rate under the OFDMA scheme. Further, Fig.4 shows that when the number of users is small, it has a greater impact on the total user rate than the big user number. For example, the total user rate increases 49.4% when the number of users increases from 10 to 20. However, the total user rate only increases 6.8% when the number of users increases from 50 to 60.

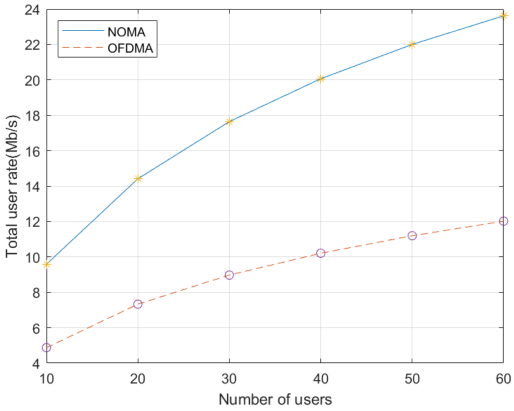

Figure 4: Comparison of the total user rate of two schemes under different number of users.

Fig.5 shows the effect of different IRS areas on the total user rate. It can be seen that when the IRS area is very small, the total user rate is quite unsatisfactory. The area of the IRS has a significant impact on the total rate which can be explained by the pathloss expression (3) as the second term which shows that the received signal power is proportional to the square of the IRS area. So, choosing a larger IRS is critical to a better system performance. However, in practice, the carrying capacity of UAV is limited. In addition, as the IRS area increases, it will affect the flight duration of the UAV. A trade-off must be made in the practical application scenarios. The figure also shows that the proposed NOMA scheme also has almost two-fold increase compared with OFDMA scheme under different IRS areas.

4 CONCLUSION

In this paper, we have proposed a UAV-assisted IRS-NOMA scheme to improve the performance of the cellular network. We have first constructed a practical system working model under two-user scenario. Then, we have used a pathloss model based on physical optics techniques to derive the received signal-to-noise ratio and throughput under two-user scenario. Finally, numerical simulation has been carried out to compare the total user rate under OFDMA scheme and NOMA scheme.

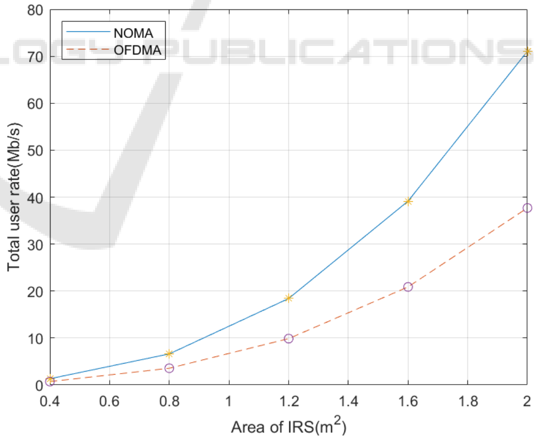

Figure 5: Comparison of the total user rate of two schemes under different IRS areas.

It has been found that using the NOMA scheme can bring almost twice the performance improvement under the same transmission power and total bandwidth. Meanwhile, we have investigated the impact of IRS area on the total user rate, where a larger IRS area will bring rapid system performance improvement, while a too-small IRS area will result in awful system performance. In further research, we will study the impact brought by mobile UAV platform, and different channel models and non-ideal IRS on the system performance.

There are several possible future works. The first is to consider the impact of UAV's position on the system performance. The second is to jointly optimize the power allocation and beamforming design to minimize the power consumption. The third is to explore the performance of IRS-NOMA with finite resolution beamforming.

REFERENCES

Z. Ding, R. Schober and H. V. Poor, "On the Impact of Phase Shifting Designs on IRS-NOMA," in IEEE Wireless Communications Letters, vol. 9, no. 10, pp. 1596-1600, Oct. 2020.

M. Fu, Y. Zhou and Y. Shi, "Intelligent Reflecting Surface for Downlink Non-Orthogonal Multiple Access Networks," 2019 IEEE Globecom Workshops (GC Wkshps), 2019, pp. 1-6.

L. Dai, B. Wang, M. Peng and S. Chen, "Hybrid Precoding-Based Millimeter-Wave Massive MIMO-NOMA With Simultaneous Wireless Information and Power Transfer," in IEEE Journal on Selected Areas in Communications, vol. 37, no. 1, pp. 131-141, Jan. 2019.

W. Hao, M. Zeng, Z. Chu and S. Yang, "Energy-Efficient Power Allocation in Millimeter Wave Massive MIMO With Non-Orthogonal Multiple Access," in IEEE Wireless Communications Letters, vol. 6, no. 6, pp. 782-785, Dec. 2017.

B. Wang, L. Dai, Z. Wang, N. Ge and S. Zhou, "Spectrum and Energy-Efficient Beamspace MIMO-NOMA for Millimeter-Wave Communications Using Lens Antenna Array," in IEEE Journal on Selected Areas in Communications, vol. 35, no. 10, pp. 2370-2382, Oct. 2017.

W. Yuan, V. Kalokidou, S. M. D. Armour, A. Doufexi and M. A. Beach, "Application of Non-Orthogonal Multiplexing to mmWave Multi-User Systems," 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), 2017, pp. 1-6.

Y. Zhao, W. Xu and S. Jin, "An minorization-maximization based hybrid precoding in NOMA-mMIMO," 2017 9th International Conference on Wireless Communications and Signal Processing (WCSP), 2017, pp. 1-6.

M. F. Sohail, C. Y. Leow and S. Won, "Non-Orthogonal Multiple Access for Unmanned Aerial Vehicle Assisted Communication," in IEEE Access, vol. 6, pp. 22716-22727, 2018.

M. F. Sohail, C. Y. Leow and S. Won, "Energy-Efficient Non-Orthogonal Multiple Access for UAV Communication System," in IEEE Transactions on Vehicular Technology, vol. 68, no. 11, pp. 10834-10845, Nov. 2019.

T. Hou, Y. Liu, Z. Song, X. Sun and Y. Chen, "Exploiting NOMA for UAV Communications in Large-Scale Cellular Networks," in IEEE Transactions on Communications, vol. 67, no. 10, pp. 6897-6911, Oct. 2019.

T. Hou, Y. Liu, Z. Song, X. Sun and Y. Chen, "Multiple Antenna Aided NOMA in UAV Networks: A Stochastic Geometry Approach," in IEEE Transactions on Communications, vol. 67, no. 2, pp. 1031-1044, Feb. 2019.

M. Liu, G. Gui, N. Zhao, J. Sun, H. Gacanin and H. Sari, "UAV-Aided Air-to-Ground Cooperative Nonorthogonal Multiple Access," in IEEE Internet of Things Journal, vol. 7, no. 4, pp. 2704-2715, April 2020.

Ö. Özdogan, E. Björnson and E. G. Larsson, "Intelligent Reflecting Surfaces: Physics, Propagation, and Pathloss Modeling," in IEEE Wireless Communications Letters, vol. 9, no. 5, pp. 581-585, May 2020.

Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li and K. Higuchi, "Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access," 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), 2013, pp. 1-5.

E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," IEEE Access, vol. 7, pp. 116753–116773, 2019.