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Deep Non-Orthogonal Multiple Access Network Assisted by Intelligent Reflecting Surface

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Abstract

The intelligent reflecting surface (IRS) assisted non-orthogonal multiple access (NOMA) symbiotic communication technology is expected to enhance the access performance, energy efficiency and spectrum efficiency of the communication network, and is regarded as an important candidate technology to support the evolution of the sixth-generation (6G) towards large-scale, high-capacity and sustainable development. However, the relevant research of this technology is still at the initial stage, and many key challenges have not been fully studied. Therefore, it is urgent to open up relevant research ideas and methods to promote its development and early implementation, so as to make it an effective 6G technology. In view of this, this paper intends to carry out the research on the theory and method of IRS assisted NOMA symbiotic transmission, starting from the analysis of the active and passive symbiotic mechanism of NOMA transmission protocol. Based on this, we further study the efficient symbiotic modulation transmission technology and multi-dimensional resource optimization allocation method. The research content of this paper is to explore the transmission theory and technology of high energy efficiency and high frequency spectrum efficiency for 6G, and break through the bottleneck problem of spectrum and energy consumption encountered by wireless communication, which has important practical significance for the wireless communication.

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1. Introduction

How to efficiently support large-scale connections and improve energy efficiency and spectrum efficiency is an important challenge to be solved in 6G networks [1–3]. Non-orthogonal multiple access (NOMA) technology allows multiple users to share the same time-frequency resource block. Therefore, compared with orthogonal multiple access (OMA), it can provide a more competitive access scheme in supporting large-scale access [4–6]. However, due to the use of serial interference cancellation technology for multi-user signal detection, the difference between multi-user channels has an important impact on the performance of NOMA [7, 8]. When the difference of channel gain of multiple users is small, the technical advantage of NOMA will be weakened, which also becomes a factor restricting the development of NOMA technology. In addition, key technologies in the fifth-generation (5G) wireless communications, such as ultra dense networking, millimeter wave communication and large-scale multiple-input multiple-output (MIMO) transmission, have certain advantages in energy efficiency and spectrum efficiency [9–11]. However, the disadvantages include complicated interference management, limitation by the physical environment, high hardware cost, and the system performance mainly depends on the complicated transceiver design. Therefore, the sixth-generation (6G) communication system needs to further study emerging transmission technologies and explore new communication paradigms in order to make breakthroughs in large-scale access, energy efficiency and spectrum efficiency, and lay a solid foundation for future green intelligence.

NOMA technology is more suitable for deployment in scenarios where there are significant differences in multi-user channel gains, but this condition does not always exist in practical communication scenarios [12–15]. Fortunately, the recently proposed intelligent reflecting surface (IRS) assisted transmission technology can artificially change the electromagnetic propagation environment, and can realize intelligent control of multi-user wireless channels with the help of intelligent controllers. This feature brings new opportunities for the development of NOMA. On one hand, IRS can be used to adjust the multi-user channel gain and create a differentiated multi-user communication environment to show the advantages of NOMA in multi-user access. On the other hand, the IRS can create a channel matching the multi-user QoS requirements, which can well overcome the mismatch between the QoS requirements and the channel quality that may exist in the traditional NOMA, thus bringing more freedom to the optimization of the NOMA network. The IRS contains a large number of controllable reflection units. By adjusting the reflection coefficient of the reflection units, considerable beamforming gain can be achieved and the communication performance can be significantly enhanced. In addition, IRS can also be used as a passive transmitter to complete data transmission by modulating information to different reflection coefficients. This type of typical application is IRS assisted symbiotic wireless communication. Symbiotic wireless transmission technology is a new type of active and passive based joint transmission architecture. Among them, passive devices, such as IRS, enhance active transmission (RF source to receiver) by reflecting RF source signals to the receiver. Meanwhile, the reflected signals (passive signals) carry additional information (usually Internet of Things (IoT) data) and can realize passive communication. It can be seen that active transmission provides communication opportunities for passive transmission, and passive transmission can also enhance active transmission, forming the reciprocal effect of active and passive transmission. In the symbiotic wireless communication system, the active and passive transmission share not only the spectrum, but also the radio frequency signal, so it shows great advantages in spectrum efficiency and energy efficiency.

In a broad sense, active and passive symbiotic transmission is also a multiple access technology, which combines IRS assisted symbiotic transmission with NOMA to form IRS assisted NOMA symbiotic wireless communication technology. This technology can further expand the number of accesses on the basis of NOMA and also enhance NOMA transmission, providing an advanced solution for 6G to achieve large-scale access with high energy efficiency and high frequency spectrum efficiency. Based on the above technical advantages, the NOMA symbiotic wireless communication technology based on IRS has important research value and practical significance. However, the research in this field is still at the initial exploration stage, and many key issues such as symbiotic transmission mechanism, system theoretical performance, efficient transmission scheme and resource optimization allocation method have not been fully studied and effectively solved. This paper will study the IRS assisted NOMA symbiotic wireless communication technology, and explore advanced multiple access technology with high energy efficiency and high spectral efficiency for the next generation wireless communication network, so as to solve the bottleneck problems encountered in the evolution of communication networks.

2. Research Progress on IRS-assisted Communication

IRS-assisted wireless communication is a new technology proposed in recent years. By adjusting the reflection coefficient (reflection amplitude and reflection phase shift) of each reflection unit, IRS can actively control the wireless channel, which provides a new degree of freedom for the design and optimization of the wireless communication system. The IRS has large-scale reflection units, and each reflection unit has the same structure. The metamaterial on the reflection unit is an artificial metal material, which can exhibit properties that natural materials do not have, such as a negative refractive index. Metamaterials are connected with active devices such as varactor diodes, PIN diodes, or switches. By changing the output voltage of active devices, the electromagnetic characteristics of metamaterials can be controlled, and the phase, amplitude, frequency, and polarization mode of incident electromagnetic waves can be also changed, that is, the reflection coefficient of IRS can be controlled. Thanks to large-scale reflection units and flexible configuration, IRS can greatly enhance wireless communication performance, such as enhancing connection and coverage, suppressing interference, etc.

The above research on IRS mainly focuses on the system design and joint optimization of transmission parameters. The existing research discusses various scenarios for IRS applications, such as physical layer security, edge user communication quality enhancement, device-to-device communication (D2D), wireless information, and energy transmission, and explores the hardware structure of IRS and the signal transmission model. The existing research investigated the IRS-assisted downstream multiuser communication system, which minimized power transmission by jointly optimizing the precoding of base stations and phase shifting parameters of IRS. The results show that low-cost IRS can achieve the same performance as large-scale MIMO. The existing research in the IRS assisted communication scenario focused on high energy efficiency design, where the energy efficiency was improved by joint optimization of transmission power and reflection factor (compared to multi-antenna relay systems). The existing research applied IRS into millimeter-wave systems to overcome severe millimeter-wave path loss and reduce coverage blindness.

In addition to theoretical research, some researches have also set up prototype systems for IRS, and have developed and tested practical communication systems. Based on the practical system, researchers designed a new type of transmitter and conducted transmission testing and path loss modeling. The researchers from MIT and NTT DOCOMO have also developed prototypes and carried out relevant tests.

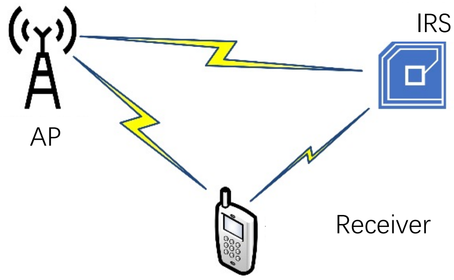

Figure 1. System model of symbiotic wireless communication

Most of the current researches are based on reflective IRS, which means that IRS can only reflect signals, but cannot transmit signals to the space behind the reflective surface, so it cannot achieve full space coverage. In order to solve this problem, the existing research proposed an IRS that can transmit and transmit simultaneously. It is characterized by the ability of each reflector to reflect the signal to the side of the RF source (i.e., the reflection function), and the signal can also penetrate the IRS to cover the back area of the reflector (i.e., the transmission function). Moreover, reflectance and transmission coefficients of IRS can be controlled independently under the law of energy conservation, which brings new degrees of freedom to the deployment and optimization of IRS, and is expected to further improve the performance of IRS-assisted communication.

3. Research progress on NOMA

In the existing researches, power-domain-NOMA has gained a lot of attention from industrial and academic researchers, and is considered as a key physical layer technology for future wireless communications. Based on the NOMA criterion, the system is able to support more user accesses than orthogonal transmission resource blocks. The technical principle of NOMA is that multiple users share the same time-frequency resource block, multiple users that multiplex the same time-frequency resource block are distinguished by power, and the receiver detects the multi-user signals sequentially in decoding order by using serial interference cancellation techniques in the existing researches. Compared to OMA, the technical advantages of NOMA are mainly 1) the ability to provide higher system capacity and cell edge user throughput, achieving better user fairness; 2) support more users to communicate simultaneously than orthogonal resource blocks, greatly enhancing the number of user accesses and facilitating the realization of large-scale access; 3) low channel feedback overhead, since only the power allocation for multiple users needs to depend on channel. Therefore, the transmitter does not need to obtain instantaneous channel state information and can complete the power allocation according to the channel gain, which can greatly reduce the channel feedback overhead.

The construction of Multiple-Input Multiple-Output (MIMO) systems by deploying multiple antennas at both ends of the transceiver can provide diversity gain, multiplexing gain, and power gain, which can significantly improve the performance of communication systems. Therefore, combining MIMO with NOMA to exploit the spatial freedom brought by multiple antennas can further improve the performance of NOMA systems in existing studies. Compared to Single-Input Single-Output (SISO)-NOMA, a new problem to be solved in MIMO-NOMA is the design of the transceiver beam. Since the performance of multi-user detection based on serial interference cancellation is highly dependent on the decoding order, unlike in SISO-NOMA where the decoding order is determined by the channel gain, in MIMO-NOMA, the decoding order needs to be designed jointly with the transceiver beam to achieve the optimal performance in the studies. The classical two-user downlink MIMO-NOMA system is considered in the study and the covariance matrix optimization problem of the transmitter is investigated with the objective of maximizing the traversal capacity given the decoding order and known channel statistical state information. In the existing research, a hierarchical transmission strategy was designed for MIMO-NOMA based on the H-BLAST (horizontal Bell Labs layered space-time) transmission architecture, where an optimal power allocation scheme was investigated to maximize the spectral efficiency of the system under the constraint of transmit power limitation, and a closed-form multiuser data rate was further derived. The user and rate maximization problem is studied in the downlink MISO-NOMA network in the existing study, and a low-complexity optimization technique for the transmit beam is designed based on the max-min algorithm. The simulation results show that NOMA has better sum-rate performance compared to OMA. In the existing study, users are divided into clusters, different clusters are served by different transmit beams, and the users in each cluster are transmitted using NOMA. Based on this transmission model, we should investigate the energy efficiency problem of MIMO-NOMA under the minimum transmission rate constraint, and propose an optimal power allocation strategy to maximize the network energy efficiency. In the existing study, large-scale MIMO is applied to NOMA to further explore the technical potential of NOMA. Specifically, a Gaussian message-passing based multi-user detection algorithm is designed for large-scale MIMO-NOMA with overload (the number of users is larger than the number of antennas at the base station), and the convergence of the algorithm is analyzed. In the existing research, secure communication techniques are investigated in large-scale MIMO-NOMA networks using artificial noise, secure transmission schemes are designed based on estimated channel state information, traversal secure rates are derived, and on this basis power allocation is optimized to maximize the system secure data rate.

Because NOMA can be combined with license-free transmission, it can increase the connection density and reduce the system overhead. Moreover, NOMA has great potential to support large-scale device access in addition to its advantages in terms of system capacity. The existing work analyzed the technical potential of NOMA in supporting large-scale IoT from an information-theoretic perspective, deriving energy-per-bit performance bounds. According to the results of the study, NOMA has significant gains over OMA. In the existing research for 6G large-scale IoT connectivity requirements, new solutions have been proposed based on NOMA, which utilize a large number of random non-orthogonal codes to reduce user conflicts and propose a series of techniques to increase the number of user accesses. In the existing research, NOMA-based semi-unauthorized transmission strategies are studied to provide potential access solutions for large-scale IoT communications, where one type of user is an authorized user while the other is a semi-unauthorized user. Specifically, we should consider to propose two contention control mechanisms to ensure accurate control of the number of users accessing the same channel, and a detailed performance analysis of the proposed scheme should be performed to reveal the superiority of the NOMA-assisted semi-unauthorized transmission strategy. Oriented to semi-unauthorized NOMA systems, the system traversal capacity in a random deployment scenario of users has been analyzed in the existing research, which uses the instantaneous received power of authorized users to select non-authorized users to form NOMA user pairs, and then derives the traversal capacity of authorized and non-authorized users, respectively. In the existing study, in order to improve the energy efficiency and BER performance of large-scale machine-like communication, a new indexed modulation technique is designed based on the NOMA transmission protocol, which uses subcarrier indexing to transmit more information and the same subcarrier to transmit multiple user information using NOMA. The results show that the energy efficiency and BER performance of the proposed transmission scheme are better than the traditional NOMA transmission scheme. Based on the NOMA transmission protocol, the performance bounds of finite-block-length coding and multi-user diversity are analyzed under Rayleigh fading multiple access channel in the existing study, revealing the technical advantages of NOMA for 6G large-scale IoT access.

In NOMA systems, the decoding order of users is often determined by the channel gain, and the decoding order determines the transmission performance of users. In conventional communication systems, the fact that the channel is immutable leads to the fact that cell edge users with small channel gains may not be able to obtain the desired transmission performance. However, combining IRS with NOMA and using IRS to achieve intelligent manipulation of the wireless channel can bring new degrees of freedom to the transmission design of NOMA. Existing research studied the IRS-assisted multi-user communication system capacity in multiple time slots with dynamic configuration of IRS, and obtained Pareto bounds for both NOMA and OMA access technologies in terms of capacity and rate by jointly optimizing the transmit power and the reflection coefficient matrix of IRS. The results show that NOMA not only achieves higher capacity gain compared to OMA, but also requires less hardware complexity for IRS. In existing research, the optimal deployment of IRS is investigated in an IRS-assisted downlink multi-user communication network by jointly optimizing the base station power allocation, the IRS reflection coefficient, and the deployment location of IRS to achieve and maximize the rate under three access mechanisms, i.e., NOMA, time-division multiplexing access (TDMA), and frequency-division multiplexing access (FDMA), respectively. Their results show that the asymmetric IRS deployment strategy is suitable for NOMA networks, while the symmetric IRS deployment strategy is suitable for OMA networks, and NOMA has significant performance advantages over TDMA and FDMA. Existing research conducted a study in IRS-assisted multi-antenna NOMA systems for transmission rate and user fairness. With the objective of maximizing the minimum received signal-to-noise ratio among all users, an optimization algorithm is designed to jointly optimize the base station transmit beam, the IRS reflection coefficient, and the user decoding order, and it is demonstrated through simulations that IRS can greatly improve the transmission performance of NOMA. In existing research, a power efficient transmission strategy is investigated in a IRS-assisted downlink MISO-NOMA network to achieve the same performance as complicated dirty paper coding (DPC) by jointly optimizing the transmit beam and IRS reflection coefficient of the base station, and simulation experiments are designed to confirm the great application potential of IRS in NOMA networks.

4. Research progress on symbiotic wireless communication based on intelligent reflecting surface

Based on the environmental backscatter technology, the concept of symbiotic radio is proposed in existing research. The existing research first explored the basic model of the symbiotic wireless communication system, as shown in Fig. 1. Its typical feature is to jointly detect the RF source signal and the signal of the environmental backscatter equipment (passive equipment) with the cooperative receiver. The symbol length of the designed passive signal is much longer than that of the active signal, so the passive signal can be regarded as the multipath component of the active communication to enhance the active transmission and realize the active passive reciprocity effect. In order to realize cellular network transmission and IoT transmission at the same time, the existing research combines symbiotic wireless transmission technology with NOMA technology, and proposes a downlink NOMA system assisted by backscatter equipment. The outage probability and ergodic capacity of the system are derived, and the diversity order of the system is analyzed. Existing researches have studied the resource allocation problem of symbiotic wireless communication systems in fading channels. By jointly optimizing the transmission power of RF sources and the reflection coefficient of passive devices, the ergodic weighted sum rate of active transmission and passive transmission can be maximized.

IRS can not only enhance the transmission performance of active communication, but also realize various modulation modes to transmit additional information by using the ability to control electromagnetic waves. With a large number of reflecting units, the IRS can aggregate more wireless energy to achieve high-performance information transmission. Therefore, using IRS to realize symbiotic wireless communication has broad application prospects and is considered as an important candidate technology for 6G to achieve high energy efficiency and high spectral efficiency. Some existing researches systematically introduce the advantages, challenges and frontier research directions of symbiotic wireless communication technology based on IRS, and look forward to the typical application scenarios of this technology. The existing research first proposed the symbiotic wireless communication system based on IRS, which creatively uses the "on-off" state of the reflection unit to encode the IoT information. The reflecting unit in the "on" state can form a passive beam to enhance the active transmission. The research results show that this transmission architecture can greatly improve the system performance compared with the traditional transmission system. Based on this, existing research further applies this novel architecture to multi-user systems. Existing research has studied the symbiotic wireless communication system assisted by IRS for the IoT communication scenario. In this system, active communication and passive communication based on IRS have respective target receivers, wherein IRS transmits IoT information through BPSK modulation, and the period of BPSK symbol is much longer than that of active transmission symbol to stimulate the active and passive effect. We should jointly optimize the beamforming parameters of active transmission and the reflection coefficient of IRS, so as to minimize the transmission power when the rate requirements of active and passive communication are met. In order to make full use of the reflection ability of IRS, orthogonal reflection modulation technology is designed to realize symbiotic transmission. The research results show that the orthogonal reflection modulation technology has better performance than the "on-off" modulation technology. Existing research designed a symbiotic wireless transmission scheme based on IRS for UAV transmission scenario, and optimized the transmission rate of IRS. Existing research also studied the multi-user MISO symbiotic wireless communication system assisted by multiple IRS based on the downlink transmission scenario. In order to maximize the active and passive weighting and rate, we should jointly optimize the active beam shaping and the reflection coefficient of the IRS under the perfect reflection condition, continuous phase condition and discrete phase condition respectively, providing guidance for the practical design of the symbiotic system. Designing spatial modulation technology based on IRS is also an important research direction to realize symbiotic wireless transmission. The IRS contains large-scale reflection units and can realize fine reflection beams, which provides a technical basis for realizing spatial modulation based on antenna index. Existing research studied the symbiotic spatial modulation technology based on IRS. Specifically, in addition to the traditional amplitude and phase based two-dimensional modulation technology, IRS also uses the receiver antenna index to transmit passive information. In order to reduce the interference between the active and passive signals, we should design a symbiotic constellation based on Star QAM. The two-dimensional amplitude and phase based signals of active and passive signals establish a one-to-one mapping relationship with the star QAM constellation. The receiver can complete the detection of active and passive signals by demodulating the star QAM signals.

5. Conclusions

To sum up, the IRS assisted NOMA symbiotic communication technology was expected to significantly improve the access performance, energy efficiency and spectrum efficiency of the communication network, and it has been regarded as an important candidate technology to support the evolution of 6G towards large-scale, high-capacity and sustainable development. However, the relevant research of this technology is still at the initial stage, and many key challenges have not been fully studied. Therefore, this paper intended to carry out the research on the theory and method of IRS assisted NOMA symbiotic transmission, starting from the analysis of the active and passive symbiotic mechanism of NOMA transmission protocol. Based on this, we further studied the efficient symbiotic modulation transmission technology and multi-dimensional resource optimization allocation method. The research content of this paper was to explore the transmission theory and technology of high energy efficiency and high frequency spectrum efficiency for 6G, and break through the bottleneck problem of spectrum and energy consumption encountered by wireless communication.

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5.2. Data Availability Statement

The authors would like to state that the readers can obtain the data of this work through the email to the authors: Dahua Ouyang (huaouyang.eecs@hotmail.com), Pingzhi Shangguan (pingshangguan.eecs@hotmail.com), Xinyong Huangfu (xinhuangpu.eecs@hotmail.com), Zenggang Linghu (zengganglinghu@hotmail.com), Haiyang Zhuge (haizhuge.eecs@hotmail.com), Haoliang Situ (haoliangsitu@hotmail.com), Shangwu Sima (shangsima@hotmail.com), Junning Shentu (junningshentu@hotmail.com), Yuanrui Xiahou (yuanruixiahou@hotmail.com), Zhengtao Helan (zhengtaohelan@hotmail.com), Zhaoyao Dongfang (zhaodongfang.eecs@hotmail.com), Kunlun Dongfang (kundongfang@hotmail.com), Zhengzhi Wanyan (zhengwanyan.eecs@hotmail.com), Qingrong Murong (qingronmuron@hotmail.com), Hanming Yuchi (hanmingweichi@hotmail.com), Zhongchun Zhangsun (zhongchunzhangsun@hotmail.com), Bingyun Helan (bingyunhelan@hotmail.com), Haida Xiahou (haixiahou@hotmail.com), Yifan Shentu (yifanshentu@hotmail.com), Weiye Sima (weiyesima@hotmail.com), Zhengfeng Situ (zhengfengsitu@sina.com), Fengqi Zhuge (fengzhug@sina.com), Jiayi Linghu (jiayilinghu@sina.com), Zhili Huangpu (zhihuangpu@sina.com), Weiyi Shangguan (weishanggua@sina.com), Shanshan Ouyang (shanouyan@sina.com), Xiatian Ouyang (xiauyang@sina.com), Zhimo Shangguan (zhishangguan@sina.com), Dechang Huangpu (dechanghuangpu@sina.com), Bozhong Linghu (bozhonglinghu@sina.com), Houjue Zhuge (houzhuge@sina.com), Yunfei Situ (yunfeisitu@sina.com), Bobo Sima (bosinma@sina.com), Zelong Shentu (zelongshentu@sina.com), Kunlun Xiahou (kunxiahou@sina.com), Zhaohui Helan (zhaohuihelan@sina.com), Siyu Wanyan (siyuwanyan@sina.com), Desheng Murong (deshengmuron@sina.com), Yingxiong Yunchi (yingxongweichi@sina.com), Baoqiang Zhangsun (baoqiangzhangsun@hotmail.com), and Jinshang Dongfang (jindongfang.eecs@hotmail.com).

5.3. Copyright

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