

A Comprehensive Performance Study of Intelligent Reflecting Surface-Enabled NOMA Communication Systems

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Abstract: Intelligent Reflecting Surfaces (IRS) has emerged as a powerful solution for enhancing the coverage and performance of wireless networks. This work investigates the integration of IRS with Non-Orthogonal Multiple Access (NOMA), where a base station transmits superimposed signals to multiple users via signal reflections from an IRS. The study evaluates the performance of IRS-assisted NOMA systems under both perfect and imperfect successive interference cancellation (pSIC and ipSIC) using a 1-bit coding scheme. Exact and asymptotic expressions are derived for the outage probability and ergodic rate of the m -th user, revealing that with pSIC, the diversity order depends on the number of reflecting elements and the user's channel position. The high-SNR slope of the ergodic rate is also analytically determined. Moreover, the throughput and energy efficiency of IRS-NOMA are assessed in both delay-limited and delay-tolerant transmission scenarios. For comparative analysis, new expressions are also derived for the outage probability and ergodic rate in IRS-assisted Orthogonal Multiple Access (IRS-OMA) systems. Numerical simulations confirm the analytical results, demonstrating that IRS-NOMA achieves superior outage performance compared to IRS-OMA and traditional relaying schemes. Additionally, the m -th user in IRS-NOMA attains a higher ergodic rate than in IRS-OMA and benchmark models, especially in the low-SNR regime, and the overall system shows significantly improved energy efficiency over conventional cooperative communication methods.

Key words: Large Intelligent Surfaces, Reflecting Surfaces, Mobile Communications MuMIMO systems

1. Introduction

Mobile communications face several persistent challenges, such as adverse weather conditions, multipath propagation, and spectrum sharing, all of which can degrade signal quality and reduce the signal-to-noise ratio (SNR). To address these limitations and improve power efficiency and spectral utilization, various technologies have been proposed. This study focuses on the benefits of

Reconfigurable Intelligent Surfaces (RIS) in enhancing SNR and overall communication performance in multi-user environments. RIS are composed of meta material-based segmented

surfaces that can reflect electromagnetic waves in a programmable manner, dynamically adjusting the phase and amplitude of incoming signals to optimize their constructive interference at the receiver. These adjustments are managed by algorithms or machine learning techniques, improving bit error rates and maintaining physical layer security. Reconfigurable Intelligent Surfaces (RIS) enhance secure communications by improving signal quality for legitimate users while reducing SNR for eavesdroppers. Their adaptability to environmental changes increases their effectiveness. RIS can be active (with signal

amplification for higher performance but more complexity) or Reconfigurable Intelligent Surfaces (RIS) enhance secure communications by improving signal quality for legitimate users while reducing SNR for eavesdroppers. Their adaptability to environmental changes increases their effectiveness. RIS can be active (with signal amplification for higher performance but more complexity) or passive (using only phase shifts). Research highlights that active RIS are efficient for optimizing SNR and energy use, while advanced concepts like intelligent surfaces (ISs) enable features like simultaneous reflection/refraction and holographic beam forming, offering high performance with low cost and energy consumption. (using only phase shifts). Research highlights that active RIS are efficient for optimizing SNR and energy use, while advanced concepts like intelligent surfaces (ISs) enable features like simultaneous reflection/refraction and holographic beamforming, offering high performance with low cost and energy consumption.

The proposed the concept of digital meta materials, which manipulates the electromagnetic waves by coding '0' and '1' elements with control sequences (i.e., 1-bit coding). Recently, several application

deployment scenarios of IRS aided were introduced that:

- i. Creating the line-of sight (LoS) link between the BS and users via signal reflection;
- ii. Applying IRS to enhance the physical layer secrecy
- iii. IRS assisted to realize SWIPT for a large amount of devices
- iv. Deploying IRS on indoor walls, mall or stadium to provide the hot spot services and so on.

The differences between IRS and active relaying such as DF relaying are mainly that IRS does not make use of any active transmitting components but only reflects the received signals to destination node through a passive array. Except these, IRS does not require self-interference cancellation operations relative to full duplex relaying which are costly to implement. Compared to DF relaying, the authors in revealed that IRS has the ability to attain the higher energy efficiency on the condition of the required large rates. The achievable rate performance of IRS assisted transmission outperformed that of DF relaying when the size of the IRS is sufficiently larger. the maximization of system throughput was formulated for IRS-NOMA by taking decoding order and reflection coefficients into consideration.

For multi-antenna scenarios, In the outage probability of nearby user for IRS-NOMA were examined by designing the passive beam forming weights of IRS [17]. Additionally, the secrecy outage performance of IRS-NOMA was evaluated in, where the use of IRS improves the security behaviours in contrast with conventional NOMA.

2. Literature Survey

In [2] authors suggested that a Multicarrier modulation could be refined depending on the optimal pulse shaping location over time, which would excrete the interference between narrowband and multipath channels. In comparison to OFDMA modulation, experiments revealed that wavelets are more efficient against narrowband interference.

In [3] authors proposed NOMA besides, a multi-antennas technology used for transmitters and recipients. Because of the spatial diversity, OFDMA can remit different independent data streams concurrently without gaining bandwidth [18]. OFDMA links various benefits to usual point-to-point connections, such as greater data speed, improved stability, highest bandwidth performance, and interference robustness. The NOMA consists of long arrays of small working antenna systems, and each consumes low power. However, it will improve the data

rate, but many low cost, low-power transceivers can replace high-performance transceivers. Large OFDMAs have shown recently to provide both chances and impediments. On the optimistic hand, as stated earlier, a large OFDMA offers several advantages over traditional.

3. Existing System

Advancement in science and technology plays a highly commendable role in the lives of humans. The technological innovations and progress will enhance the quality of life and plays an important aspect for the healthy living, will help life of human beings to be social and communicate with others. The decade's progress in wireless technology had brought revolutionary changes in the life style of people living in this earth [19]. This progress is highly appreciable. The changes in signal characterization have brought a demand for the various innovations and developments in the wireless communication system [20]. The type and property of signal used will determine the wireless technology and which will in turn lead to the improvement in the various performance parameters of the wireless system. Environmental conditions significantly impact signal characteristics by introducing attenuation, interference, and other effects that degrade signal quality [21]. To mitigate such challenges, modern wireless systems

employ techniques like Orthogonal Frequency Multiple Access (OFMA), which divides frequency-selective (FS) channels into multiple flat sub-channels, enabling simpler one-tap equalization to reduce multipath effects. Combined with MIMO (Multiple Input Multiple Output), OFMA enhances spatial multiplexing and throughput, and is widely used in technologies such as WLAN and LTE. In high-speed communication systems, issues like Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) arise due to multipath delays, Doppler shifts, and fastvarying channels. While cyclic prefixes can mitigate ISI, Doppler effects still cause ICI and degrade subcarrier orthogonality. Solutions like Doppler estimation using training sequences or linear frequency modulation exist, but they often increase complexity, power consumption, and reduce data rates, making them less suitable for real-time applications. The existing system faces several limitations that impact its performance and reliability. One major issue is the inability to accurately estimate improper or varying channel conditions, which leads to inefficient signal processing and degraded communication quality. Additionally, high levels of noise further deteriorate signal clarity, reducing overall system efficiency. The system also suffers

from diversity problems, limiting its ability to effectively utilize multiple signal paths for improved reliability and throughput.

4. Proposed Method

Non-Orthogonal Multiple Access (NOMA) is emerging as a key technology for 5G networks, offering higher spectral efficiency compared to traditional Orthogonal Multiple Access (OMA) systems, especially under poor channel conditions. By leveraging power domain multiplexing and Successive Interference Cancellation (SIC), NOMA allows multiple users to share the same time and frequency resources. However, user association and power control pose significant challenges. To address this, evolutionary algorithms like Grey Wolf Optimizer (GWO) are used for optimal power allocation, outperforming legacy approaches such as Particle Swarm Optimization (PSO). This study also explores IRS-assisted NOMA networks in a vehicular communication scenario, analysing performance under imperfect and perfect SIC. Key contributions include deriving outage probability and ergodic rate expressions, showing that IRS-NOMA outperforms IRS-OMA and traditional relaying methods in terms of outage behavior, ergodic rate, and energy efficiency. Results indicate that deploying IRS close to the base station improves

performance, and that IRS-NOMA systems achieve significant energy and throughput gains in both delay-limited and delay-tolerant modes.

At this moment, the wireless links considered in IRS-NOMA networks are modeled as Rayleigh fading channels and our future work will relax this idealized simplifying assumption. These wireless links are perturbed by additive white Gaussian noise (AWGN) with the mean power N_0 simultaneously. Since the channel estimation and feedback process are not the consideration of this manuscript, we assume that perfect channel state information, geographic location information at the BS and perfect feedback information to the IRS can be achieved carefully.

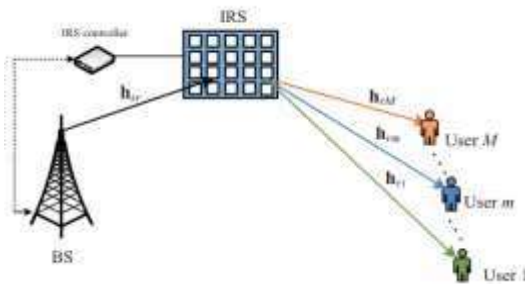


Fig 1: IRS-assisted downlink NOMA network model

Therefore, one DF relay is assumed to be located between the BS and vehicle 2, which leads to two phases for transmission from the BS to vehicle 1 and vehicle 2. To enable this two-phase transmission, we investigate two

relaying transmission schemes, C-NOMA-GQSM with GWO optimization as shown in Figure 1.

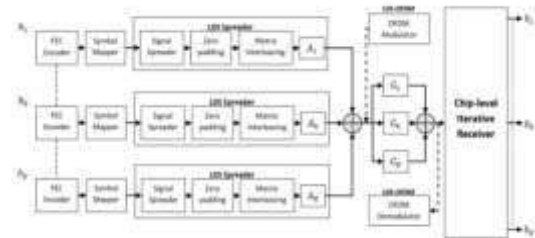


Fig.2: Proposed system model.

1) We derive exact and asymptotic expressions of outage probability for the m -th user with ipSIC and perfect successive interference cancellation (pSIC) in IRS-NOMA networks. Based on theoretical analyses, the diversity order for IRS-NOMA is obtained. We

demonstrate that the diversity orders of the m th user with ipSIC/pSIC are in connection with the number of reflecting elements of IRS and channel ordering. We also derive the closed form expression of outage probability for IRS-assisted OMA.

2) We confirm that the outage behaviours of IRS-NOMA are superior to that of IRS-OMA, AF relaying and FD/HD DF relaying. Furthermore, we investigate the impact of IRS's deployment on the outage behaviours of IRS NOMA networks. We observe that when the IRS is deployed closely to the BS, the enhanced outage performance is achieved. As the IRS departs from BS, the LoS deteriorates and the outage probability increases.

3) We derive the exact expressions of ergodic rate of the m-th user for IRS-NOMA networks. To obtain further more insights, we derive exact expression of ergodic rate for the m-th user and obtain the high SNR slopes. We observe that the ergodic rate of the m-th user converges to a throughput ceiling in the high SNR regime. As the number of reflecting elements increase, the ergodic performance of the M-th user is becoming higher compared to relaying schemes. We also derive exact expression of ergodic rate for IRS-OMA 4) We study the throughput and energy efficiency of IRS-NOMA networks in both delay-limited and delay tolerant transmission modes. For delay-limited transmission mode, the energy efficiency of IRS-NOMA outperforms that of IRS-OMA and converge to a constant value at high SNRs, while the IRSNOMA and IRS-OMA achieve the larger energy efficiency than AF relaying and FD/HD DF relaying. In delay-tolerant transmission mode, the energy efficiency of IRS-NOMA is much larger than that of these benchmarks.

The architecture model of the proposed method in NOMA-GQSM based systems is demonstrated in fig. 2, which still needs two phases to complete the whole transmission. It should be noted that vehicle 1 is near to the BS, and the DF relay is relatively far from the BS, which leads to $\sigma^2_{BV1} > \sigma^2_{BR}$. Due to the NOMA principle, the BS will combine

two signal vectors by $x_{ALL} = \sqrt{\zeta_1}x_1 + \sqrt{\zeta_2}x_2$,

where ζ_1 and ζ_2 denote the power allocation factors for vehicle 1 and vehicle 2, respectively, and $\zeta_1 + \zeta_2 = 1$ as the transmit power constraint. Since vehicle 1 is near to the BS and vehicle 2 as well as the relay are far from the BS, the BS will allocate more power to user 2 (x_2) and less power to vehicle 1 (x_1) by NOMA, which leads to $\zeta_1 < \zeta_2$. By C-NOMA-GQSM, the BS first broadcasts the combined signal x_{ALL} to both vehicle 1 and the relay in the first phase. The $N_r \times 1$

$$\begin{aligned} y_{BV1}^{NOMA} &= \mathbf{H}_{BV1}x_{ALL} + \mathbf{n}_{BV1} \\ &= \mathbf{H}_{BV1}(\sqrt{\zeta_1}x_1 + \sqrt{\zeta_2}x_2) + \mathbf{n}_{BV1} \end{aligned}$$

$$\begin{aligned} y_{BR}^{NOMA} &= \mathbf{H}_{BR}x_{ALL} + \mathbf{n}_{BR} \\ &= \mathbf{H}_{BR}(\sqrt{\zeta_1}x_1 + \sqrt{\zeta_2}x_2) + \mathbf{n}_{BR} \end{aligned}$$

received signal vectors at vehicle 1 and the relay can be expressed as

(1)

(2)

Respectively, where \mathbf{n}_{BV1} and \mathbf{n}_{BR} denote the the $N_r \times 1$ noise vectors following the distribution $CN(0, \sigma^2_{BV1})$ and $CN(0, \sigma^2_{BR})$, respectively.

The working analysis of Intelligent Reflecting Surface (IRS)-assisted NOMA under multipath fading channels using a 1-bit coding scheme focuses on enhancing signal transmission efficiency and reliability with minimal hardware complexity. In this setup,

the IRS reflects incoming signals with phase shifts quantized to just 1-bit, simplifying the implementation while still effectively improving the received signal strength. Despite the coarse phase resolution, IRS can still combat multipath fading by constructively aligning reflected paths. When integrated with NOMA, this approach enables simultaneous user support with different power levels, while successive interference cancellation (SIC) is applied at receivers. Analytical results show that even with 1-bit coding, IRS-assisted NOMA achieves notable improvements in outage probability, ergodic rate, and energy efficiency, proving its viability in resourceconstrained and interference-prone environments. **5. Results**

The numerical results are presented to confirm the rationality of the derived theoretical expressions for IRS-NOMA networks. We show the impact of the reflecting elements on the performance of the IRS-NOMA communication network. To simulate the effects of RIS on the channel, the Monte Carlo method was used to estimate the statistics of the resulting channel, generating random variables iterations and comparing the histogram with the theoretical probability density function; the bit error probability and SOP were obtained analytically through the simulated SINR.

Considering $K=8$ users, $M=16$ antennas at the transmitter, and the von Mises concentration parameter $\kappa=2$, it is possible to observe in Figures that the SINR follows the gamma distribution obtained with the parameters calculated from the channel statistics. It is also noteworthy that with the increase in the number of reflectors, higher SINR values are more likely, as can be seen in the distribution.

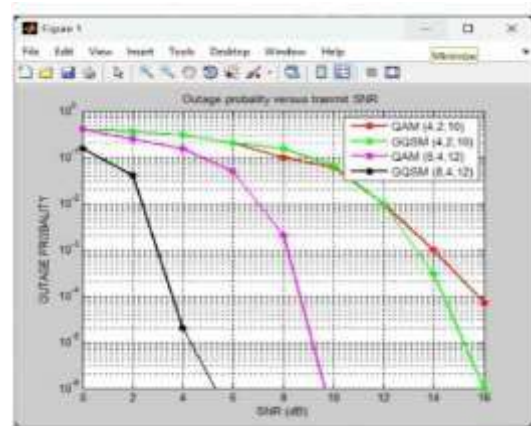


Fig 3: Outage Probability Vs. with SNR

The graph compares the performance of traditional QAM and QPSM schemes based on outage probability versus transmit SNR. It shows that QPSM consistently achieves lower outage probabilities than QAM, especially at low to moderate SNR levels. This highlights QPSM's higher reliability and efficiency, making it a better option for communication systems with bandwidth or power limitations.

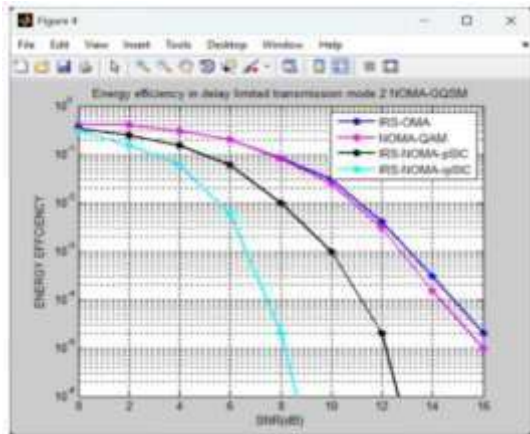


Fig 4: Energy Efficiency Based On Transmission Delay

The figure compares the energy efficiency of various communication schemes with respect to SNR. Among them, IRS-NOMA-pSIC shows the best performance, maintaining high energy efficiency across all SNR levels, while

IRS-NOMA-ipSIC performs the worst, dropping sharply after 6 dB. This indicates that integrating IRS with NOMA and partial SIC greatly improves energy efficiency, making it ideal for energy-limited wireless networks.

6. Conclusion & Future work

In this project, an IRS has been invoked in downlink NOMA networks, where 1-bit coding scheme is taken into account. We have derived the exact expressions of outage probability and ergodic rate for users with ipSIC/pSIC for IRS-NOMA networks. Based on the approximated analyses, the diversity order of the m -th user is related to the number of reflecting elements and channel ordering. Due to the interference from the nearby users'

signals, a zero of high SNR slope for ergodic rate is obtained by the distant users. Simulation results showed that the outage behaviors of IRS-NOMA are superior to that of IRSOMA, AF relaying and FD/HD DF relaying. The nearest user has a larger ergodic rate than orthogonal user and distant users. The throughput and energy efficiency of IRS-NOMA were discussed both in delay-limited and delaytolerant transmission modes. The setting of single antenna and Rayleigh fading channel may give rise to overestimated performance for IRS-NOMA, hence our future work will consider these complicated assumptions.

Another promising future research direction is to design the beamforming combined power allocation, which will further enhance the performance of IRS-NOMA.

Future work: For improving the MIMOW-NOMA system, an integrated approach of maximum likelihood (ML) equalizer based ICI mitigation implements for 5th generation wireless networks. Thus, the bit error rate of MIMO-W-NOMA system improves and reduces the processing delay and complexity as well

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