Enabling Joint Sensing and Communication via STBC Assisted NOMA in ISAC Systems

Anindya Bal*, Haofan Cai*, Hanqing Guo*, Yao Zheng* and Xiaoxue Zhang†

*Dept. of Electrical and Computer Engineering, University of Hawaii at Mānoa, HI, USA
Email: anindyab@hawaii.edu, haofanc@hawaii.edu, guohanqi@hawaii.edu, yao.zheng@hawaii.edu

† Dept. of Computer Science and Engineering, University of Nevada, Reno, NV, USA
Email: xzhan330@ucsc.edu

***Abstract*—Integrated Sensing and Communication (ISAC) is a key enabler for Sixth-Generation (6G) and future wireless networks, which seamlessly combines ambient sensing with data communication. In this paper, we propose a novel ISAC-enabled Non-Orthogonal Multiple Access (NOMA) scheme named ISAC-Space-Time Block Coding (STBC) NOMA. We present a thorough performance comparison of our proposed scheme against three previously studied ISAC-NOMA variants: Conventional ISAC-NOMA, ISAC-Unmanned Aerial Vehicle (UAV) NOMA, and ISAC-Generalized Space Shift Keying (GSSK) NOMA, in a multi-user scenario. The comparison specifically focuses on three critical performance metrics: spectral efficiency, Bit Error Rate (BER), and Successive Interference Cancellation (SIC) decoding complexity. The evaluation results show that ISAC-STBC NOMA consistently outperforms the other schemes across all metrics. Specifically, ISAC-STBC NOMA achieves approximately 24% higher spectral efficiency at 30 dB Signal-to-Noise Ratio (SNR), reduces the BER by approximately 30%, and lowers SIC decoding complexity by up to 25%. These findings position ISAC-STBC NOMA as a strong candidate for next-generation networks, offering a well-balanced solution that enhances communication robustness, spectrum utilization, and computational efficiency.**

***Index Terms*—STBC-NOMA, ISAC NOMA, Bit Error Probability, Spectral Efficiency, Successive Interference Cancellation.**

I. Introduction

The rapid advancement of wireless communication has driven the evolution toward sixth-generation (6G) networks, which are designed to support massive connectivity while integrating advanced capabilities such as environmental sensing, intelligent automation, and ultra-reliable communication to address the growing demand for high-speed, low-latency wireless services [1] [2]. To meet these lofty objectives, Integrated Sensing and Communication (ISAC) has become a key enabling technology, allowing wireless networks to effectively use the same spectrum for both sensing and communication tasks [3]. By offering real-time environmental awareness without compromising data transmission performance, ISAC is expected to play a significant role in applications including autonomous cars, industrial automation, and next-generation IoT systems.

In addition, non-orthogonal multiple access (NOMA) has emerged as a crucial multiple access method for improving user connection and spectral efficiency in 6G networks. Unlike conventional orthogonal multiple access (OMA), which assigns distinct frequency or time resources to different users, NOMA employs power-domain multiplexing and successive interference cancellation (SIC) to allow numerous users to share the same time and frequency resources. While this approach significantly improves network capacity and spectrum utilization, it also introduces challenges related to power distribution, decoding complexity, and interference control. Integrating NOMA with ISAC presents both technical challenges and opportunities in developing interference-resilient and energy-efficient wireless systems [4] [5].

In this work, we propose a groundbreaking ISAC-enabled NOMA scheme named ISAC-Space-Time Block Coding (STBC) NOMA, which combines STBC with NOMA to enhance spectral efficiency, robustness, and communication reliability in next-generation wireless networks. To the best of our knowledge, this is the first study to introduce STBC into the ISAC-NOMA framework, aiming to overcome key challenges such as multipath fading, limited diversity gain, and uneven user fairness in wireless networks. To validate the proposed scheme, we conduct a comprehensive analytical and simulation-based performance evaluation against three representative ISAC-NOMA variants that have been systematically analyzed in earlier studies [6]: baseline ISAC-NOMA, ISAC-GSSK NOMA, and ISAC-UAV NOMA. All schemes are benchmarked under consistent system configurations to ensure fair comparison.

To provide a comprehensive evaluation, we consider a multi-user scenario with ten communication users and one sensing target, and assess the performance of these schemes in terms of spectrum efficiency, energy efficiency, outage probability, and the number of Successive Interference Cancellation (SIC) operations needed for signal decoding. The results reveal that ISAC-STBC NOMA consistently outperforms existing schemes, by reducing SIC complexity while maximizing spectral and energy efficiency. Its ability to effectively manage interference and optimize diversity gains using STBC makes it a prime contender for the next high-density, low-latency 6G networks.

The remainder of this paper is organized as follows: In Section II, the relevant literature is discussed, emphasizing previous studies on ISAC-NOMA tactics. Section III details the system model, including key assumptions, channel models, and NOMA configurations. In Section IV we present a detailed numerical analysis of the proposed systems, along with theoretical formulations and comparison metrics. A comprehensive simulation analysis is provided in Section V, together with results and discussions derived from the numerical results. Section VI concludes the study by summarizing key findings, while outlines potential research directions to further advance ISAC-NOMA systems.

II. Related Works

In addition to supporting emerging applications such as environmental awareness, autonomous mobility, and intelligent industrial systems, 6G wireless networks are envisioned to achieve unprecedented advancements in connectivity, latency, and spectral efficiency. A critical enabler in fulfilling these goals is the integration of sensing and communication, commonly referred to as integrated sensing and communication (ISAC), which utilizes shared frequency bands for simultaneous data transmission and environmental perception [1]. Meanwhile, non-orthogonal multiple access (NOMA) has gained traction as a robust solution to accommodate massive connectivity demands by enabling multiple users to share the same time-frequency resources. NOMA employs power-domain multiplexing and successive interference cancellation (SIC) to achieve higher spectral efficiency compared to conventional orthogonal multiple access (OMA) systems [1], [4]. However, these benefits often come at the cost of increased decoding complexity and interference management challenges.

Several recent works have attempted to combine ISAC and NOMA to leverage the strengths of both. Backscatter-enabled and reconfigurable intelligent surface (RIS)-assisted ISAC-NOMA systems have been studied to show how resource reuse and user clustering can lead to improvements in both energy and spectrum efficiency [2]. Additionally, hybrid NOMA frameworks have been proposed for energy-efficient ISAC by adapting power allocation strategies to balance dual sensing and communication functions [4].

Despite these advancements, traditional ISAC-NOMA frameworks still face critical limitations. Baseline ISAC-NOMA structures, as explored in earlier works such as [7], suffer from poor spectral efficiency due to susceptibility to multipath fading. An improvement has been proposed through generalized space shift keying (GSSK), where ISAC-GSSK NOMA encodes information using active antenna indices, boosting spectral efficiency. However, this method is particularly vulnerable in densely deployed networks or in low signal-to-noise ratio (SNR) conditions, as observed in [8], [9], and [10]. Another promising development, ISAC-UAV NOMA, introduces unmanned aerial vehicles as relays to enhance coverage for edge users. This method, while extending reach, leads to higher latency and elevated levels of interference [7], [11], [12], [13].

Nonetheless, none of the existing frameworks fully address the trio of requirements essential for scalable 6G deployment: enhanced spectrum efficiency, manageable SIC complexity, and improved communication diversity. To address this gap, we propose a new approach called ISAC-STBC NOMA. This model integrates space-time block coding (STBC) into the NOMA framework, mitigating fading effects and promoting better link reliability. Although prior works such as [5] have examined the potential of STBC in NOMA with GSSK and UAV extensions, the combination of STBC with ISAC-NOMA in a comparative analysis remains unexplored. This study builds upon the foundational models of power allocation, user decoding order, and signal-to-interference-plus-noise ratio (SINR)-based performance metrics previously discussed in the literature [8], [9], [13], extending them toward a more resilient and scalable ISAC-NOMA system.

III. System Model

A. Model Formulation

In the proposed system model, we consider a ISAC system that uses NOMA in conjunction with STBC as illustrated in Figure 1. This model primarily focuses on a scenario where a dual-functional base station (BS) euipped with M antennas simultaneously communicates with a group of K_c 1-antenna communication users (CUs) and senses with K_s sensing targets (STs). The set of CU and ST are denoted by $\mathcal{U}_c = \{u_1, u_2, ..., u_{K_c}\}$ and $\mathcal{T}_s = \{t_1, t_2, ..., t_{K_s}\}$, respectively. Based on their proximity to the BS, CUs are further classified into two groups: near users (NUs) and cell-edge users (FUs). In our study, we consider a system comprises 1 ST, denoted by $\mathcal{T}_s = \{t_1\}$, 2 NUs, denoted by $\mathcal{U}_N = \{u_1, u_2\}$ and 8 FUs, denoted by $\mathcal{U}_F = \{u_3, u_4, \ldots, u_{10}\}$ (as shown in Fig. 1). It is noted that the system can also accommodate varying number of users and targets.

Different from conventional NOMA, NU can actually act as a mobile 'relay node' in the proposed system. Take u_1 as an example, based on u_1's location relative to BS and FUs, the system can be described under the following 2 cases as shown in Fig. 1:

- In case 1, u_1 moves close enough to the group of FUs, and acts as a relay node. u_1 initially receives robust, diversity-enhanced signals from the ISAC BS, then forwards these enhanced signals to the FUs using a NOMA protocol (ISAC-STBC NOMA phase). This relay action significantly boosts the FUs' ability to receive clear and reliable signals even under challenging propagation conditions.
- In case 2, if u_1 fails to relay the entire intended data correctly and completely to FUs, or if u_1 remains at a close distance from BS, the system initiates a fallback strategy. In this fallback scenario, BS directly transmits the remaining or lost parts of the data to the FUs through conventional NOMA technique (Direct NOMA Phase).

Similarly, u_2 can also act as a relay node interchangeably. When u_1 moves too far from FUs, causing it to be ineffective or unreliable in relaying signals, u_2 immediately assumes the relay responsibility. This relay-assisted interaction plays a crucial role in mitigating the signal degradation experienced by FUs

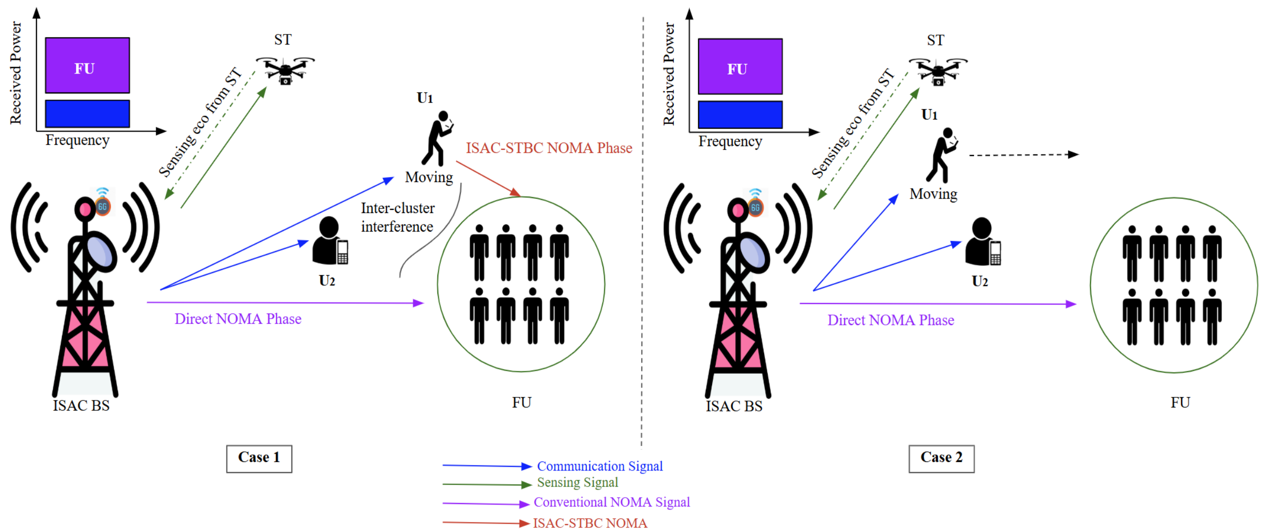

Fig. 1. ISAC-STBC NOMA system model

due to their distance from the BS, thereby enhancing overall communication reliability and system efficiency.

The channel between the BS and communication user u_k is characterized by channel state $\mathbf{H}_k$. Due to their proximity to the BS, NUs have better channel conditions than FUs:

$$\|\mathbf{H}_i\|^2 > \|\mathbf{H}_j\|^2, \quad \forall u_i \in \mathcal{U}_N, u_j \in \mathcal{U}_F. \tag{1}$$

1) Communication Model: In order to simultaneously serve all the users, the BS adopts the power domain NOMA, meaning that FUs who have poorer channel conditions are allocated with higher power, whereas NUs who have better channel conditions will receive lower power from BS. Therefore, BS transmits the superimposed signal x as follows:

$$x = \sqrt{P_N} s_N + \sqrt{P_F} s_F, \tag{2}$$

where s_N and s_F represent symbol vectors for NUs and FUs, and P_N and P_F denote transmission powers assigned to NUs and FUs, respectively, with $P_N > P_F$. The received signal at user u_k is:

$$y_k = \mathbf{H}_k x + n_k. \tag{3}$$

where $n_k \sim \mathcal{CN}(0, \sigma^2)$ represents additive white Gaussian noise (AWGN).

For NUs, a specialized STBC scheme [5] is employing to improve signal reliability, hence $\mathbf{s}_N$ also represents NUs' data stream's STBC-encoded symbol matrix. $\mathbf{s}_N$ is created from two data symbols and sent across two antennas over two time slots using a 2×2 Alamouti scheme [5]. NUs further perform SIC to decode the received signal. For u_1, decoding occurs as:

$$\hat{s}_{u_1} = \arg\min_{s_{u_1}} \|y_1 - \mathbf{H}_1 \sqrt{P_{u_1}} s_{u_1}\|^2, \tag{4}$$

followed by the decoding of u_2 after subtraction:

$$y_1' = y_1 - \mathbf{H}_1 \sqrt{P_{u_1}} \hat{s}_{u_1}, \quad \hat{s}_{u_2} = \arg\min_{s_{u_2}} \|y_1' - \mathbf{H}_1 \sqrt{P_{u_2}} s_{u_2}\|^2. \tag{5}$$

For FUs, the system functions in two primary stages, the ISAC-STBC NOMA phase and the direct NOMA phase, as shown in Fig. 1. In the direct NOMA phase, BS communicates with the FUs that are located at the edge of the cell. Unlike the NUs that benefit from STBC, the FUs receive signals directly from ISAC BS and are subject to more severe propagation impairments, including path loss, shadowing, and multipath fading.

Each FU u_j receives a superimposed signal composed of all user data streams. Let $\mathbf{h}_j \in \mathbb{C}^{1 \times M}$ be the channel vector from the BS (with M antennas) to FU u_j, and s_k is the data intended for FU u_k. The received signal at FU u_j is given by:

$$y_j = \mathbf{h}_j \sum_{k \in \mathcal{U}_F} \sqrt{P_k} s_k + n_j, \tag{6}$$

where P_k is the power allocated to user u_k, and $n_j \sim \mathcal{CN}(0, \sigma^2)$ is AWGN. To decode their desired signal, FUs apply SIC. Assume that the users are ordered by increasing channel quality, such that:

$$\|\mathbf{h}_3\|^2 \leq \|\mathbf{h}_4\|^2 \leq \cdots \leq \|\mathbf{h}_{10}\|^2. \tag{7}$$

User u_j decodes and subtracts signals of users u_k with $k < j$, treating $k > j$ as interference. The decoding of signal s_k at u_j is expressed as:

$$\hat{s}_k = \arg\min_{s_k} \left\| y_j - \sum_{l=1}^{k-1} \mathbf{h}_j \sqrt{P_l} \hat{s}_l - \mathbf{h}_j \sqrt{P_k} s_k \right\|^2. \tag{8}$$

After applying SIC, the SINR for decoding s_j at user u_j is:

$$\text{SINR}_j = \frac{|\mathbf{h}_j \sqrt{P_j}|^2}{\sum_{l=j+1}^{10} |\mathbf{h}_j \sqrt{P_l}|^2 + \sigma^2}. \tag{9}$$

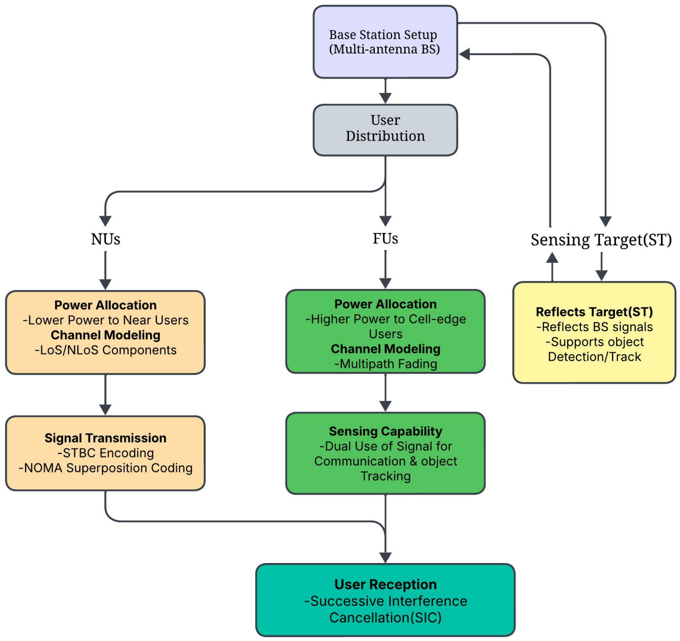

Fig. 2. Flowchart of the system

In the ISAC-STBC NOMA phase, the SINR for decoding s_j at user u_j is:

$$R_{j,\text{STBC}} = \log_2\left(1 + \frac{P_j N_t |h_j|^2}{\sum_{k=j+1}^{10} P_k N_t |h_k|^2 + N_0}\right) \tag{10}$$

where N_t is the number of transmit antennas in the STBC system.

Although STBC is not applied in the direct NOMA phase for FUs, the combination of optimized power allocation and SIC enables reliable communication. This strategy maximizes spectral efficiency and user fairness while supporting a high number of cell-edge users under shared time-frequency resources.

2) Sensing Model: For sensing, the BS analyzes echoes from transmitted signals. If $\mathbf{H}_1^{(echo)}$ denotes the echo channel from sensing target t_1, the sensing signal received at the BS is:

$$y_{BS}^{(sensing)} = \mathbf{H}_1^{(echo)} s_{t_1} + n_{BS}, \tag{11}$$

which can be used for tasks like localization and tracking.

By outlining the essential elements of power allocation, channel modeling, signal transmission, and sensing capabilities, the flowchart (Fig. 2) illustrates the ISAC system's actual implementation procedure. In order to compensate for increasing route loss, the system allocates more power to FUs and less power to NUs. FUs' channel modeling takes into consideration real-world multipath fading conditions by combining both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) components. STBC encoding and NOMA superposition coding are used at the signal transmission stage to allow for simultaneous multi-user access over shared spectrum. Crucially, the sensing capacity allows for dual functioning without the need for extra sensing infrastructure by using the same broadcast signals for both data transfer and object tracking.

B. Problem Formulation

The objective of this work is to maximize the total spectral efficiency while ensuring: (i) each user u_k's SINR meets a minimum threshold $\gamma_k^{\min}$; (ii) sensing fidelity is achieved by guaranteeing sufficient power from sensing target t_1's reflected signal; and (iii) SIC decoding complexity remains below a certain limit. The problem is formulated as:

$$\max_{\{P_k\}} \left(\sum_{k=1}^{K} \log_2(1 + \text{SINR}_k) - \lambda C_{\text{SIC}}\right) \tag{12}$$

subject to:

$$\text{SINR}_k \geq \gamma_k^{\min}, \quad \forall k \in \{1, \ldots, K\} \tag{13}$$

$$\sum_{k=1}^{K} P_k \leq P_{\text{total}} \tag{14}$$

$$P_1 |\tilde{h}_1|^2 \geq \Gamma_{\text{sense}} \tag{15}$$

$$C_{\text{SIC}} \leq C_{\max} \tag{16}$$

Here, λ is a weighting factor that penalizes excessive SIC decoding complexity C_{SIC}, Γ_{sense} is the minimum required sensing signal strength from sensing target t_1, and $\tilde{h}_1$ is the echo channel gain for sensing.

C. Proposed Solution

To support the performance of the proposed ISAC-STBC NOMA system, we present a mathematical derivation based on the optimization objective and constraints. The system aims to maximize the total spectral efficiency while ensuring minimum SINR thresholds, satisfying a sensing power constraint, and limiting SIC decoding complexity. In a power-domain NOMA setting, each user's SINR depends on power allocation and decoding order. Assuming users are ordered in ascending channel gain and that SIC is applied accordingly, the SINR for user u_k can be expressed as

$$\text{SINR}_k = \frac{P_k \|h_k\|^2}{\sum_{j=k+1}^{K} P_j \|h_k\|^2 + \sigma^2}, \tag{17}$$

which reflects that a user treats the signals of stronger users (higher in the decoding order) as interference while cancelling those of weaker users. In the proposed design, power is allocated inversely to channel gain, such that $P_k = \alpha \cdot \|h_k\|^{-2}$, where α is a scaling factor. Substituting this into the SINR expression yields

$$\text{SINR}_k = \frac{\alpha}{\sum_{j=k+1}^{K} \alpha + \sigma^2 / \|h_k\|^2}, \tag{18}$$

which ensures that even users with poor channels can meet their SINR thresholds by receiving proportionally more power. To satisfy the sensing fidelity constraint, the BS must receive a sufficient signal reflection from sensing target t_1. The required condition is $P_1 |\tilde{h}_1|^2 \geq \Gamma_{\text{sense}}$, where $\tilde{h}_1$ is the echo channel gain and Γ_{sense} is the sensing SNR threshold. Substituting the power allocation into the constraint gives

$$\alpha \cdot \frac{|\tilde{h}_1|^2}{\|h_1\|^2} \geq \Gamma_{\text{sense}}, \tag{19}$$

which provides a lower bound on α to ensure that the sensing constraint is met. The communication latency for user u_k transmitting a payload of size D is defined as $T_k = \frac{D}{R_k}$, where $R_k = \log_2(1+\text{SINR}_k)$. Substituting this into the latency expression gives

$$T_k = \frac{D}{\log_2(1 + \text{SINR}_k)}, \tag{20}$$

demonstrating that as SINR_k increases, latency decreases. This effect is further improved by the use of STBC, which enhances SINR through spatial diversity. For instance, with an Alamouti STBC scheme across two antennas, the effective SINR becomes

$$\text{SINR}_k^{\text{STBC}} = \frac{1}{2} \sum_{m=1}^{2} \frac{P_k \|h_{k,m}\|^2}{\sigma^2}, \tag{21}$$

which provides a gain over single-antenna transmission and reduces the probability of retransmissions, contributing to latency reduction. Finally, SIC decoding complexity increases with the number of layers a user must decode. For user u_k, the number of decoding steps is proportional to $K - k$. The total SIC complexity can therefore be approximated as

$$C_{\text{SIC}} = \sum_{k=1}^{K} w_k (K - k) \tag{22}$$

where w_k is an optional weight to reflect user priority. This term is penalized in the objective function via the regularization weight λ, discouraging excessive SIC depth in the power allocation solution.

By using orthogonal pathways to transmit signals across many antennas and time slots, STBC reduces interference across clusters. Overlapping transmissions may cause inter-cluster interference when u_1 relays data to distant users. However, this is mitigated with the use of scheduling tools and STBC [13]. During the ISAC-STBC NOMA phase, Far user's SINR is described in eq(10). When combined with dynamic relay switching, STBC's orthogonality reduces detrimental interference between user groups. The SINR increases to the following when STBC is utilized over two antennas:

$$\text{SINR}_j^{\text{STBC}} = \frac{P_{\text{relay}} \cdot \sum_{m=1}^{2} |h_{j,1}^{(m)}|^2}{P_{\text{BS}} \cdot |h_{j,\text{BS}}|^2 + \sigma^2} \tag{23}$$

The interference gain is as follows, assuming the BS utilizes beamforming and θ_j is the angle between the BS beam and user u_j:

$$G(\theta_j) = \frac{\sin(N\pi d \cos(\theta_j))}{N \sin(\pi d \cos(\theta_j))} \tag{24}$$

With beamforming, the interference-aware SINR becomes into:

$$\text{SINR}_j^{\text{STBC+BF}} = \frac{P_{\text{relay}} \cdot \sum_{m=1}^{2} |h_{j,1}^{(m)}|^2}{P_{\text{BS}} \cdot G(\theta_j)^2 \cdot |h_{j,\text{BS}}|^2 + \sigma^2} \tag{25}$$

The inter-cluster interference brought on by many base station broadcasts is specifically modeled by this equation. The benefit of STBC, which combines many separate fading routes to increase the received signal intensity through spatial diversity, is reflected in the numerator. The influence of beamforming is taken into account in the denominator, which illustrates how directed broadcast from the base station may decreases interference at receivers end.

IV. Numerical Analysis

Spectral efficiency, SINR, and Bit Error Probability for ISAC NOMA, ISAC-STBC NOMA, ISAC-UAV NOMA, and ISAC-GSSK NOMA are all thoroughly mathematically analyzed in this section. The special characteristics of each scenario are examined, along with how they improve the efficiency of wireless communication.

TABLE I

Symbol	Description
P_k	Power allocated to user k
h_k/h_j	Channel gain for user k, j
N_0	Noise power
K	Total number of users
SINR_k	Signal-to-Interference-plus-Noise Ratio
R_k	Spectral efficiency of user k
$Q(\cdot)$	Q-function (Gaussian error probability)
N_t	Number of transmit antennas
G_A	Antenna array gain
h_{STBC}	Channel gain in STBC
h_{UAV}	Channel gain in UAV communication
h_{GSSK}	Channel gain in GSSK
d	Distance between transmitter and receiver
h_{UAV}	UAV altitude
β_0	Reference path loss coefficient
α	Path loss exponent
$\sum_{j=k+1}^{K} P_j \|h_j\|^2$	Total interference from higher index users

A. ISAC NOMA (Baseline Model)

The basic paradigm is the ISAC NOMA, in which power-domain multiplexing is enabled by allocating various power levels to many users. Stronger users (those closer to the base station) employ SIC to decipher their signals and are given less power. In the ISAC NOMA system, a user k's SINR is calculated as follows [14]:

$$\text{SINR}_k = \frac{P_k |h_k|^2}{\sum_{j=k+1}^{K} P_j |h_j|^2 + N_0} \tag{26}$$

This formula is calculated taking into account that each user's received power is made up of interference from lesser users as well as the desired power from its allotted amount. Higher index users, who receive more power but have worse channel conditions, are the source of the overall interference. The spectral efficiency for ISAC NOMA is defined by the Shannon capacity theorem as follows [15] [12]:

$$R_k = \log_2(1 + \text{SINR}_k) \tag{27}$$

It measures the number of bits per second per Hz that each user can attain with the specified SINR. The Q-function is used to calculate the bit error probability for a BPSK or QPSK modulation method under Rayleigh fading [16]:

$$P_b = Q\left(\sqrt{2 \cdot \text{SINR}_k}\right) \tag{28}$$

where the standard normal distribution's tail probability is denoted by Q(x). Better system dependability is indicated by a lower BER, which is correlated with a higher SINR value. The foundation for further improvements like STBC, UAV support, and GSSK is provided by this basic model.

B. ISAC-STBC NOMA (Space-Time Block Coding for Enhanced Diversity)

Enhancing diversity gain through the use of STBC across numerous transmit antennas is the main objective of ISAC-STBC NOMA. By distributing signals among several antennas, STBC increases a signal's resilience to fading. When using N_t transmit antennas in an STBC system, the effective channel gain is:

$$h_{\text{STBC}} = \sqrt{N_t} h_k \tag{29}$$

This indicates that the number of transmit antennas has a proportionate effect on the channel gain. As a result, the SINR is likewise improved, which results in:

$$\text{SINR}_{k,\text{STBC}} = \frac{P_k N_t |h_k|^2}{\sum_{j=k+1}^{K} P_j N_t |h_j|^2 + N_0} \tag{30}$$

The spectral efficiency directly improves as a result of the gain being increased by N_t, and this may be stated as follows:

$$R_{k,\text{STBC}} = \log_2\left(1 + \frac{P_k N_t |h_k|^2}{\sum_{j=k+1}^{K} P_j N_t |h_j|^2 + N_0}\right) \tag{31}$$

Utilizing STBC has the advantage of counteracting small-scale fading, which produces SINR values that are more stable. The bit error rate is further decreased by this stability, which is expressed using the improved Q-function:

$$P_b = Q\left(\sqrt{2 \cdot N_t \cdot \text{SINR}_k}\right) \tag{32}$$

Here, the exponential decay in BER suggests that STBC significantly reduces errors as the number of transmit antennas increases. By leveraging spatial diversity, ISAC-STBC NOMA ensures a more reliable transmission, particularly beneficial in environments where channel fading is severe.

C. ISAC-UAV NOMA (UAV-Assisted Communication for Coverage Extension)

In order to improve the signal strength for distant users, the ISAC-UAV NOMA scheme incorporates UAVs into the communication infrastructure. For customers with substantial route loss, UAVs serve as flying base stations or relays, hence enhancing connection. The equation for a UAV-assisted link's route loss model is as follows [11]:

$$h_{\text{UAV}} = \frac{\beta_0}{(d^2 + h_{\text{UAV}}^2)^{\frac{\alpha}{2}}} \tag{33}$$

It takes into consideration the UAV's altitude h_{UAV} and the distance d between it and the user. When a user receives communication from a UAV, their SINR is [12]:

$$\text{SINR}_{k,\text{UAV}} = \frac{P_k |h_{\text{UAV},k}|^2}{\sum_{j=k+1}^{K} P_j |h_{\text{UAV},j}|^2 + N_0} \tag{34}$$

Additionally, the bit error probability is increased when the UAV improves the channel conditions [13]:

$$P_b = Q\left(\sqrt{2 \cdot \text{SINR}_{\text{UAV},k}}\right) \tag{35}$$

UAV placement optimization improves signal quality, lowers BER, and increases dependability for remote users.

D. ISAC-GSSK NOMA (Generalized Spatial Shift Keying for Spectral Efficiency Enhancement)

The ISAC-GSSK NOMA system uses antenna indices to transmit extra data by utilizing GSSK. This results in an extra antenna array gain G_A in the system as the base station not only modulates signals but also chooses which antenna or antennas to activate. In ISAC-GSSK NOMA, the effective channel gain is [8]:

$$h_{\text{GSSK}} = G_A h_k \tag{36}$$

This includes antenna selection improvements and beamforming. As a result, SINR expression is increased as [9]:

$$\text{SINR}_{k,\text{GSSK}} = \frac{P_k G_A |h_k|^2}{\sum_{j=k+1}^{K} P_j G_A |h_j|^2 + N_0} \tag{37}$$

The fact that ISAC-GSSK NOMA boosts spectral efficiency without raising bandwidth needs is one of its main benefits. This is accomplished by use antenna indices to encode extra bits, which yields [10]:

$$R_{k,\text{GSSK}} = \log_2\left(1 + \frac{P_k G_A |h_k|^2}{\sum_{j=k+1}^{K} P_j G_A |h_j|^2 + N_0}\right) + \log_2 N_t \tag{38}$$

where the additional information bits carried by the antenna index are taken into account by the additional $log_2\ N_t$ term. In ISAC-GSSK NOMA, the bit error probability is determined by [10]:

$$P_b = Q\left(\sqrt{2 \cdot G_A \cdot \text{SINR}_k}\right) \tag{39}$$

It shows that beamforming improvements and spatial variety have significantly increased reliability.

V. SIMULATION ANALYSIS

In this section, we present the comprehensive simulations to evaluate the performance of the proposed model. ISAC-STBC NOMA model is compared with three ISAC-based NOMA variants: ISAC-UAV NOMA, ISAC-GSSK NOMA, and baseline ISAC NOMA. Key performance metrics, including spectral efficiency, SINR and bit error rate (BER), are analyzed under various antenna configurations (2, 4, 8, and 12 transmit

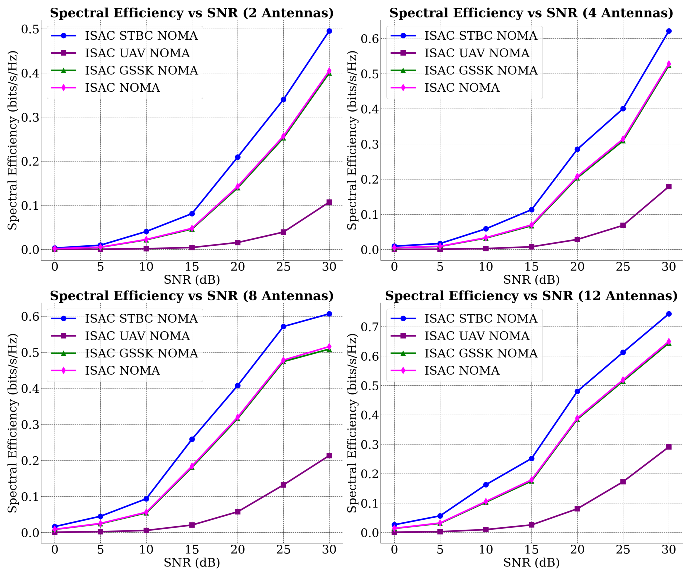

Fig. 3. Spectral efficiency comparison for various number of transmitted antennas.

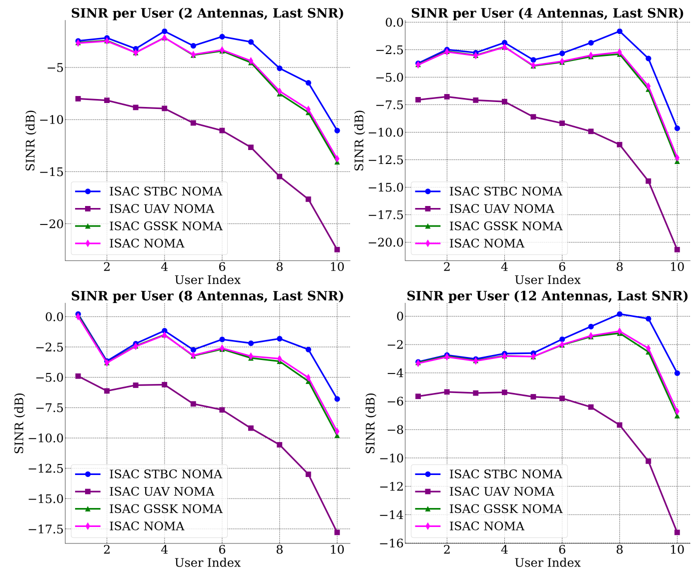

Fig. 4. SINR per user comparison for different ISAC NOMA variants

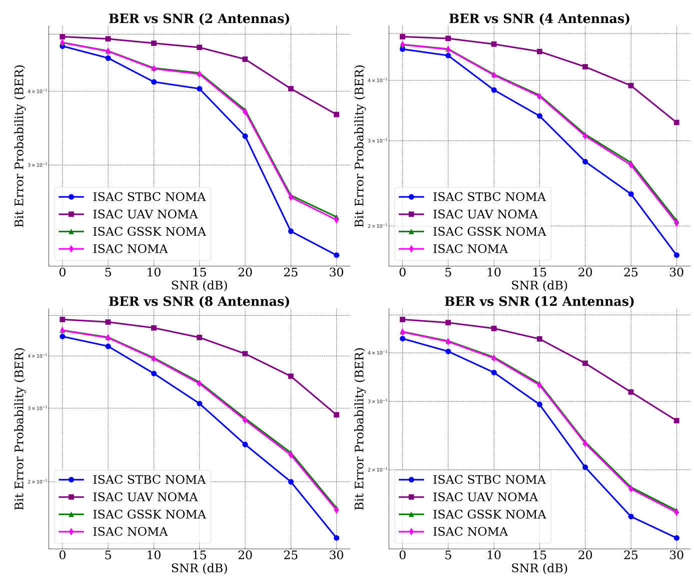

Fig. 5. BER performance comparison of ISAC NOMA variants

antennas). To ensure a realistic assessment, the simulations incorporate critical wireless propagation factors such as path loss, multipath fading, and interference, which are prevalent in next-generation networks. Through this comprehensive numerical evaluation, we aim to highlight the theoretical advantages of each scheme and show the superiority of our proposed model for optimizing spectral efficiency, communication reliability, and overall system performance.

Fig. 3 shows the spectral efficiency of four ISAC-based NOMA schemes—ISAC-STBC NOMA, ISAC-UAV NOMA, ISAC-GSSK NOMA, and baseline ISAC NOMA— under various SNR situations (0 to 30 dB) and different transmit antenna configurations (2, 4, 8, and 12 antennas). The numerical results demonstrate that ISAC-STBC NOMA consistently outperforms the other schemes. Notably, at high SNR (30 dB) with 12 antennas, ISAC-STBC NOMA achieves a spectral efficiency of approximately 5.5 bits/s/Hz, whereas ISAC-UAV NOMA, ISAC-GSSK NOMA, and baseline ISAC NOMA saturate around 2–3 bits/s/Hz. The performance gap becomes increasingly pronounced as the number of antennas grows—while the difference is marginal with 2 antennas, ISAC-STBC NOMA exhibits a statistically significant advantage at 12 antennas. The spatial diversity of STBC, which distributes signals over several antennas to counteract deep fading, is the source of this performance improvement. STBC raises effective channel gain and improves signal resilience by establishing distinct spatial routes, which raises SINR. According to Shannon's capacity theorem, this enhancement in SINR translates into increased achievable data rates. Thus, ISAC-STBC NOMA effectively uses spatial diversity to greatly improve spectral efficiency at all taken SNR values, both theoretically and numerically.

We illustrate the SINR distribution for users indexed by their proximity to the base station in Fig. 4, with closer users experiencing stronger channel conditions and distant users subjected to weaker channel conditions. Across all antenna configurations, ISAC-STBC NOMA continuously shows better SINR performance for all users, particularly benefiting far users. For instance, in the 12-antenna scenario, distant users (indices 8–10) achieve SINR values around -7 to -8 dB under ISAC-STBC NOMA. In contrast, these users experience severe signal degradation under other three schemes, where their SINR drops significantly to values below -12 to -17 dB, leading to poor link quality and reduced communication reliability. STBC offers both temporal and spatial redundancy by transmitting multiple signal copies across antennas and time slots. This enhances signal strength at the receiver and mitigates multipath fading. In ISAC-STBC NOMA, such diversity improves SINR for far users with low power, boosting QoS, fairness, and signal reliability across the network.

Fig. 5. shows the variation in BER performance under different antenna configurations (2, 4, 8, and 12 antennas) across an SNR range of 0–30 dB. ISAC-STBC NOMA routinely outperforms ISAC-UAV NOMA, ISAC-GSSK NOMA, and the standard ISAC NOMA scheme in reducing BER. Notably, while other schemes struggle to lower BER beyond 3×10^{-1} to 4×10^{-1}, ISAC-STBC NOMA, particularly with 12 antennas, achieves a significantly lower BER, dropping below 2×10^{-1} at an SNR level of 30 dB. This shows that ISAC-STBC NOMA's connection robustness and reliability have improved noticeably. The diversity order of STBC, in which several antennas independently produce fading signal copies, is its theoretical foundation. By averaging out fading, constructive combining at the receiver lowers the likelihood of bit errors and improves channel dependability. Better BER performance indicates that STBC increases power efficiency through antenna diversity as opposed to just raising power.

VI. Conclusion

In this work, we propose a novel ISAC scheme, ISAC-STBC NOMA, which combines STBC with NOMA to enhance spectral efficiency, robustness, and communication reliability in next-generation wireless networks. By exploiting spatial-temporal diversity, ISAC-STBC NOMA significantly outperforms existing schemes including ISAC-UAV NOMA, ISAC-GSSK NOMA, and baseline ISAC-NOMA. The inclusion of STBC enables effective mitigation of multipath fading and substantial improvements in SINR, especially for far users, while also lowering the BER and supporting higher data rates under constrained bandwidth conditions. Our results demonstrate that ISAC-STBC NOMA consistently outperforms the other schemes, achieving significantly higher spectral efficiency (up to 24%), lower BER (reduced by 30%), and reduced SIC complexity (up to 25%). These advantages make ISAC-STBC NOMA particularly well-suited for real-world applications such as industrial IoT, emergency public safety systems, vehicle-to-everything (V2X) communications, and telemedicine—where consistent, low-latency, and high-reliability connectivity is crucial. Moreover, through SIC performance and optimized resource utilization, ISAC-STBC NOMA demonstrates strong potential for energy-efficient and scalable deployment in dense and dynamic 6G environments.

Future research can build on this work by investigating adaptive power allocation, physical-layer security enhancements, and the integration of AI/ML techniques for intelligent interference and antenna management. Experimental validation on software-defined radio (SDR) platforms, extension to massive MIMO and heterogeneous network (HetNet) environments, and compatibility with emerging technologies such as Reconfigurable Intelligent Surfaces (RIS), THz/mmWave bands, and aerial communication systems will further position ISAC-STBC NOMA as a cornerstone for the evolution of integrated sensing and communication in 6G and beyond.

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